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Milvich

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(54) **INDUCED CURRENT POSITION TRANSDUCERS HAVING IMPROVED SCALE LOOP STRUCTURES**

(75) Inventor: **Michelle M. Milvich, Seattle, WA (US)**

(73) Assignee: **Mitutoyo Corporation, Kawasaki (JP)**

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(52) **U.S. Cl.** **324/207.17; 324/207.24; 324/207.25; 336/45; 336/129; 340/870.32**

(58) **Field of Search** **324/207.12, 207.15-207.19, 324/207.24, 207.25, 239-243; 336/45, 73, 75, 77, 79, 115, 129; 340/870.32, 870.34-870.36**

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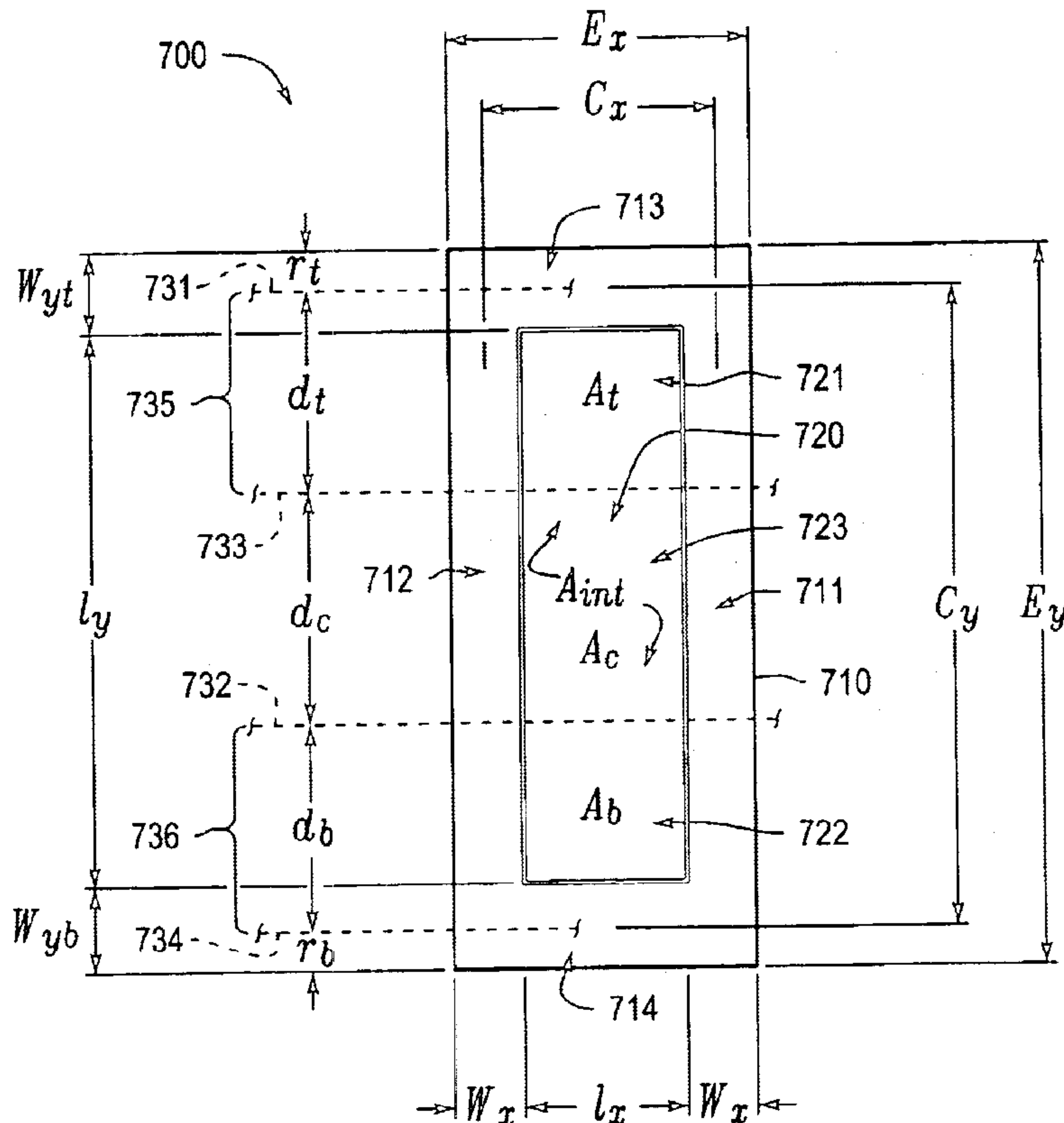
Primary Examiner—Gerard R. Strecker

(74) *Attorney, Agent, or Firm*—Oliff & Berridge, PLC

(57) **ABSTRACT**

A scale loop formed by a loop trace of electrically conductive material is usable in an induced current position transducer. The scale loop is continuous and has a particular shape depending on the configuration of the induced current position transducer. The scale loop is not in contact with other highly conductive materials. The dimensions of the cross-section of the conducting trace are chosen to increase the transfer of energy through the transducer.

27 Claims, 10 Drawing Sheets



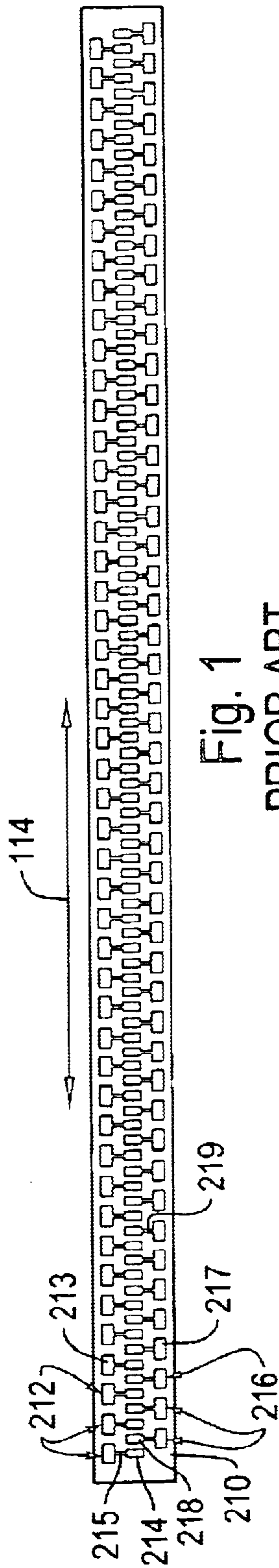


Fig. 1
PRIOR ART

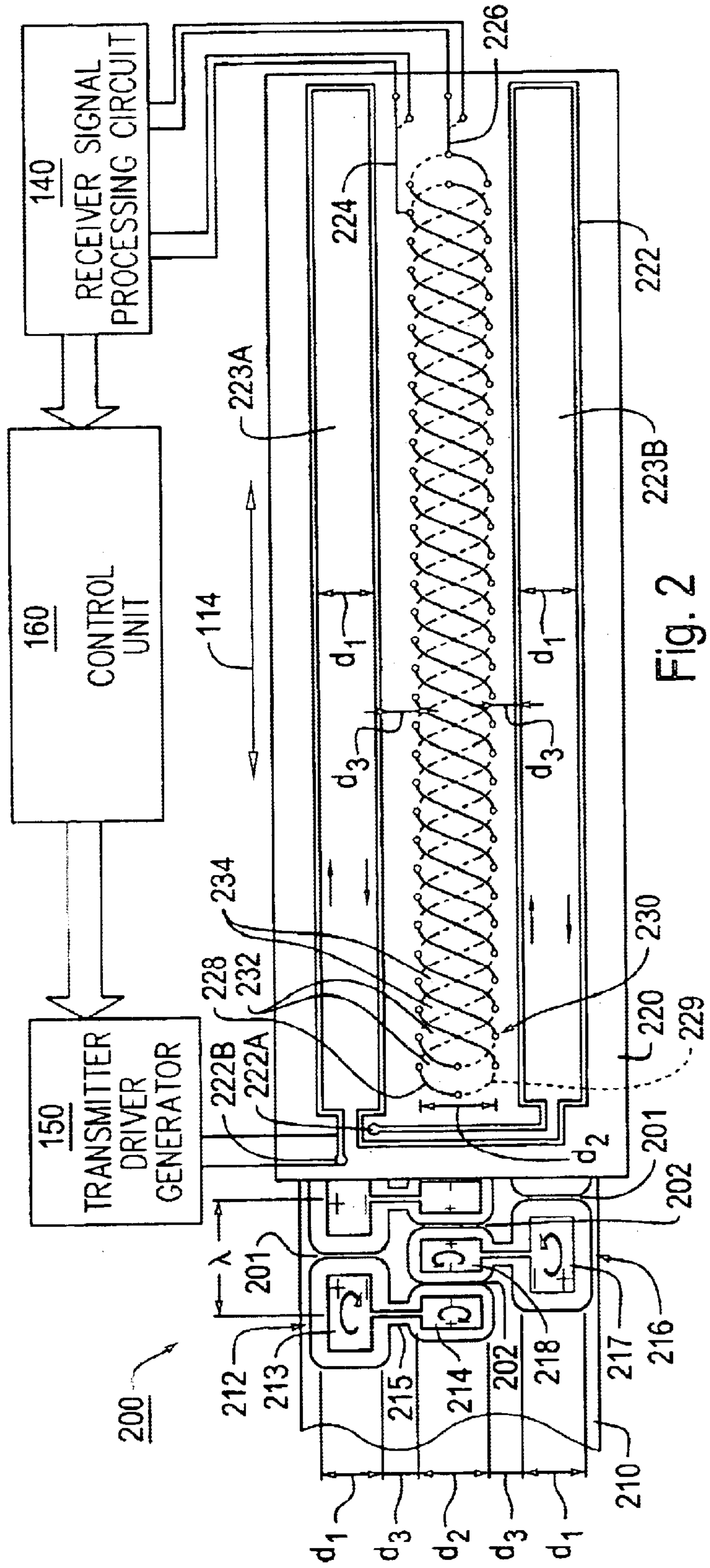


Fig. 2
PRIOR ART

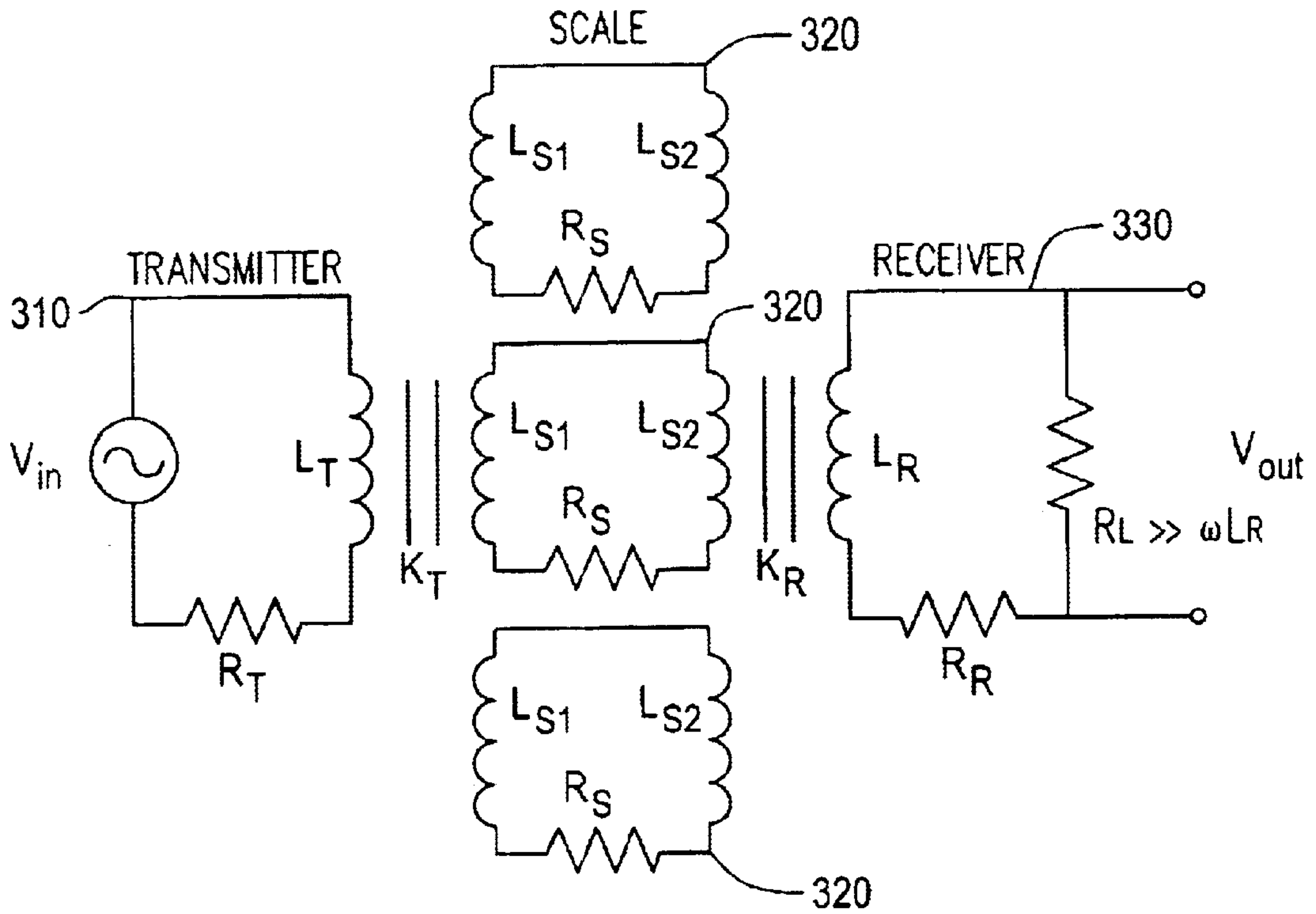


Fig. 3

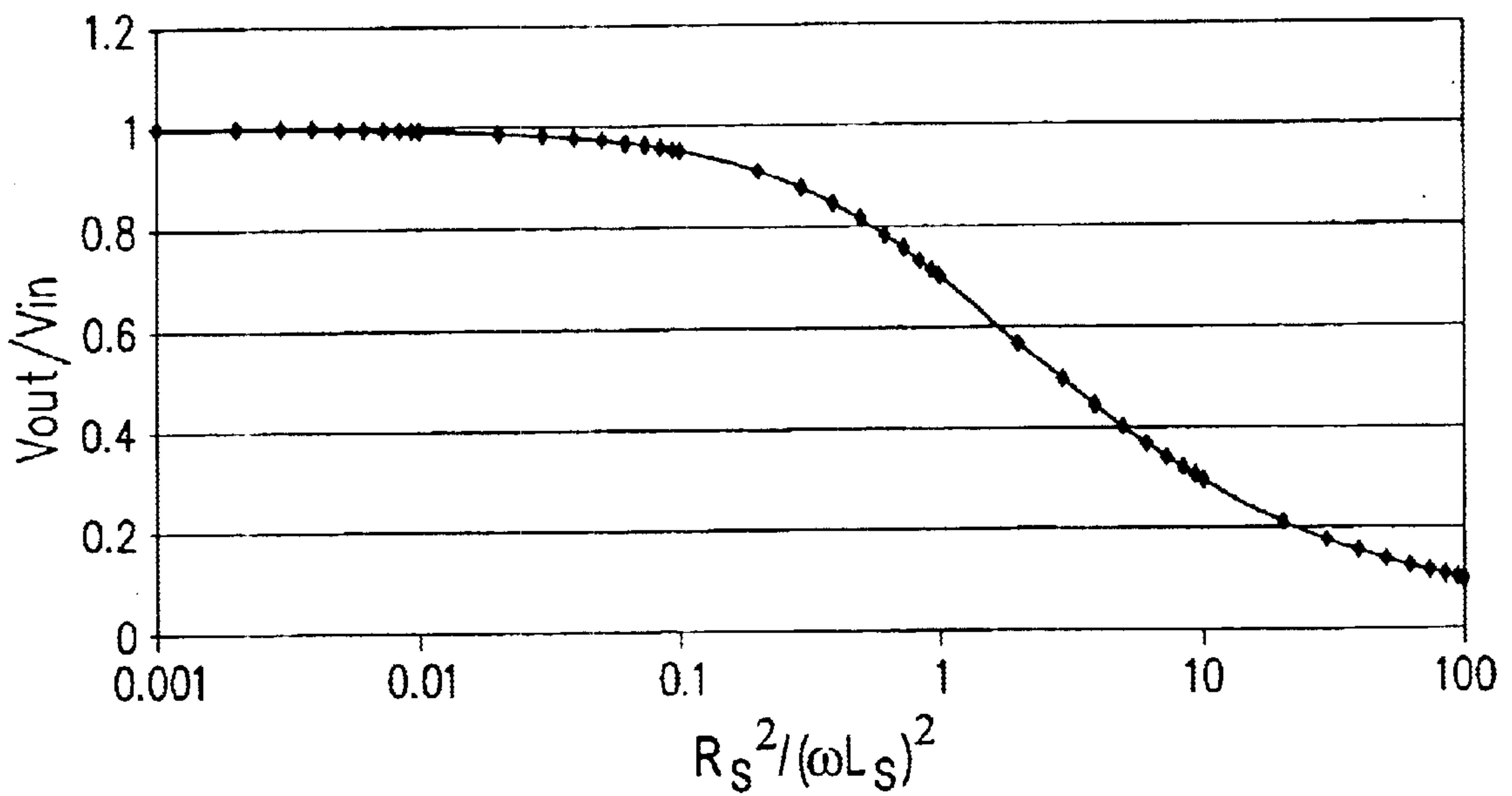


Fig. 4

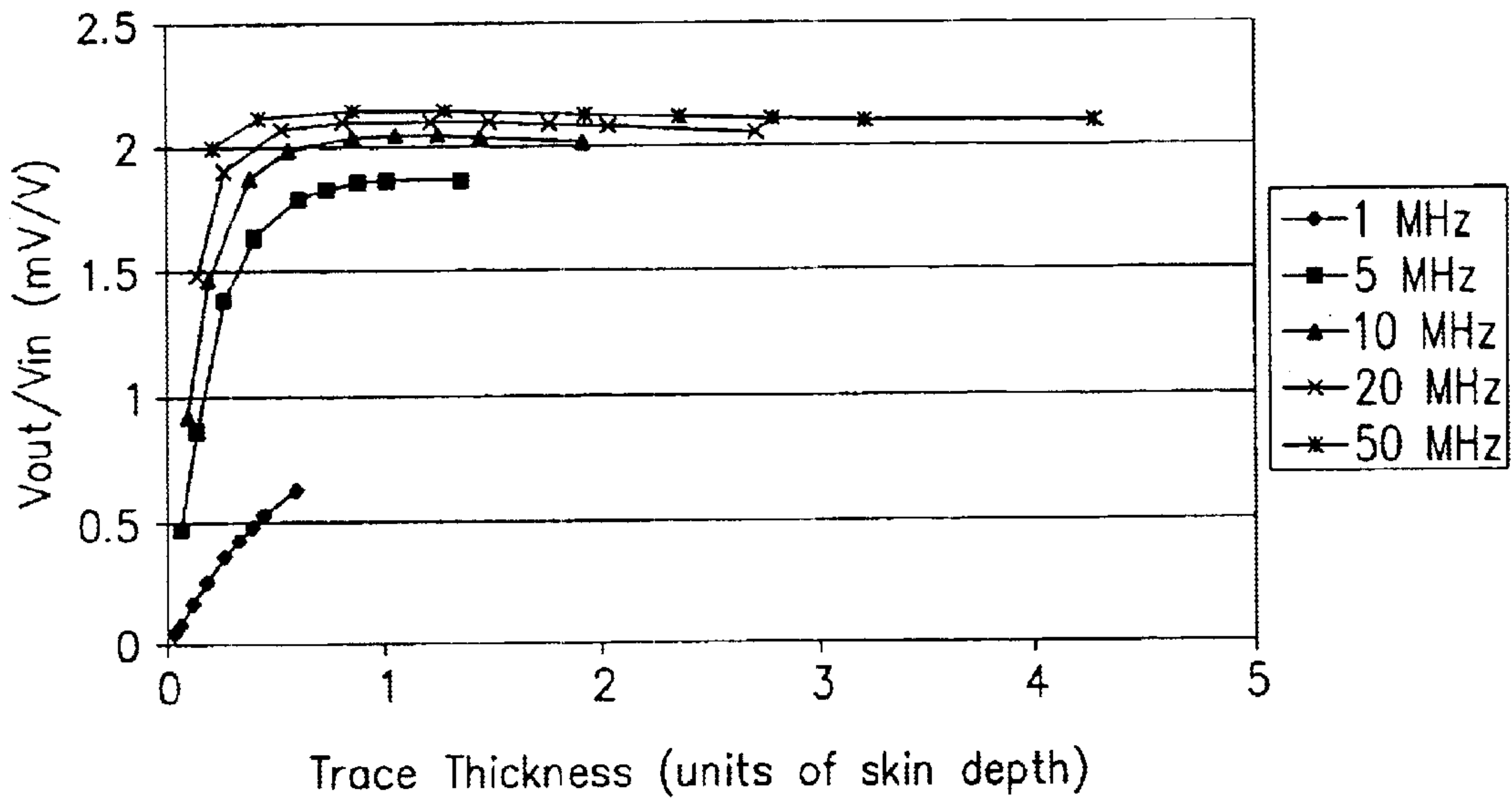


Fig. 5

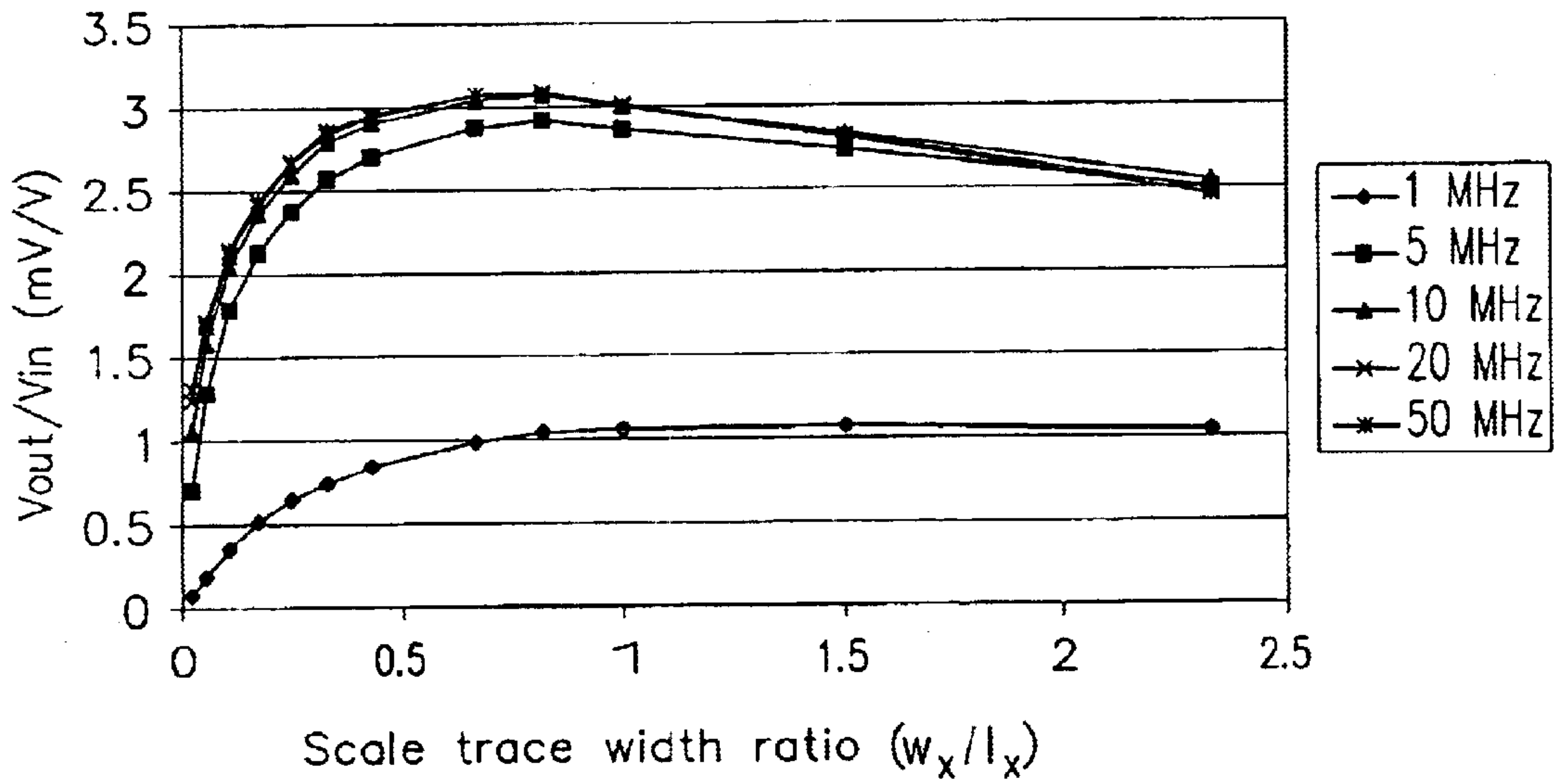


Fig. 6

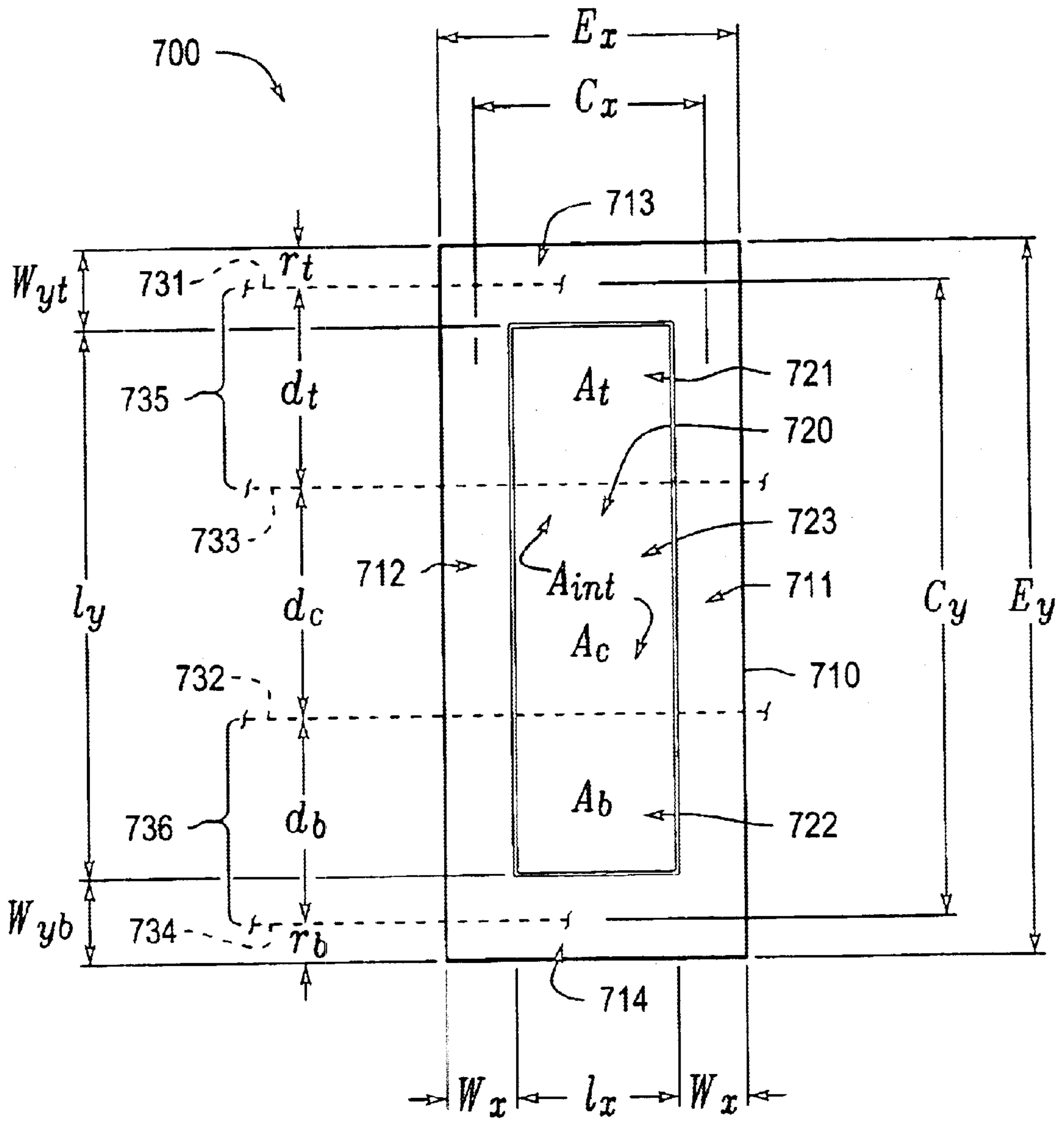


Fig. 7

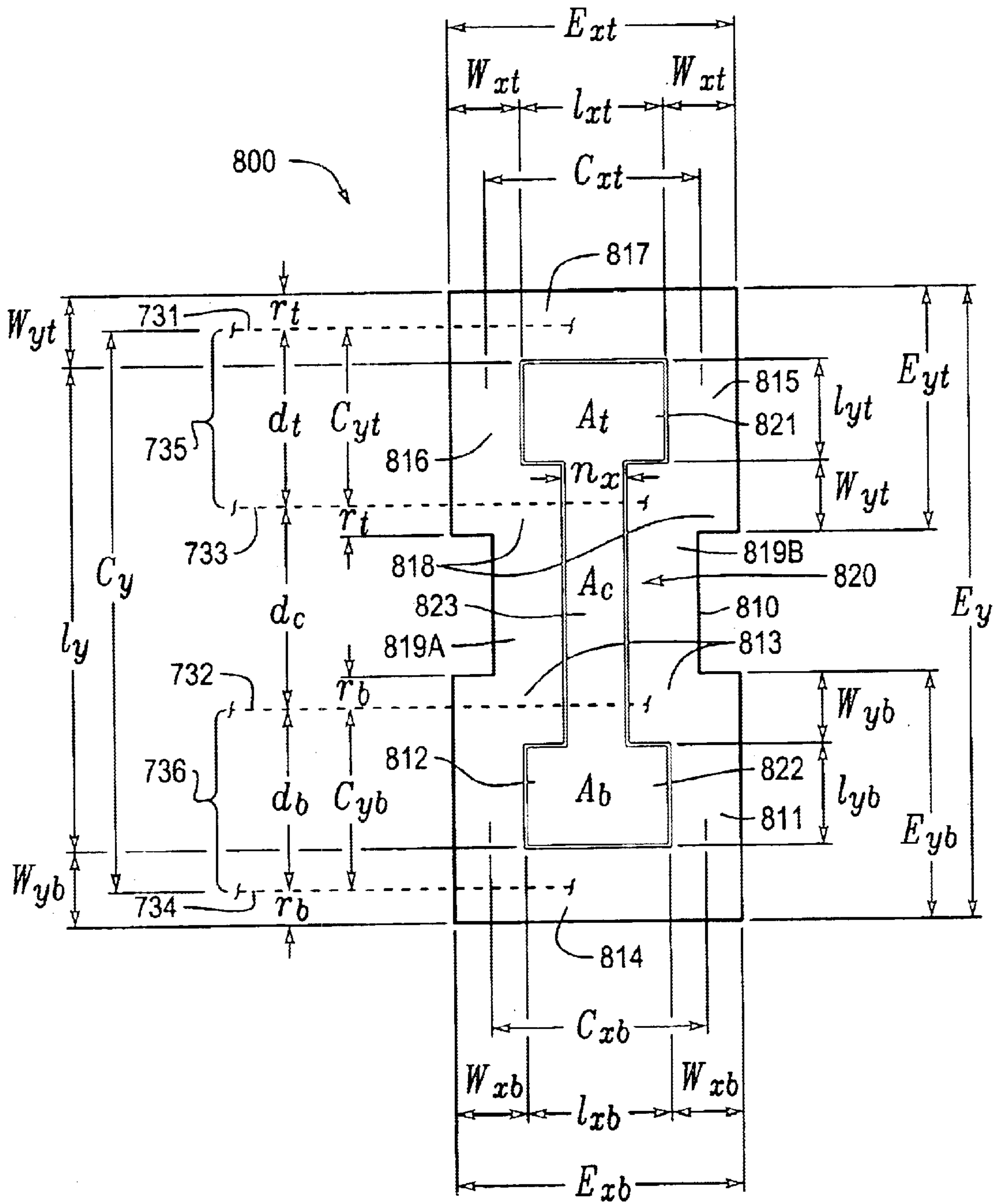


Fig. 8

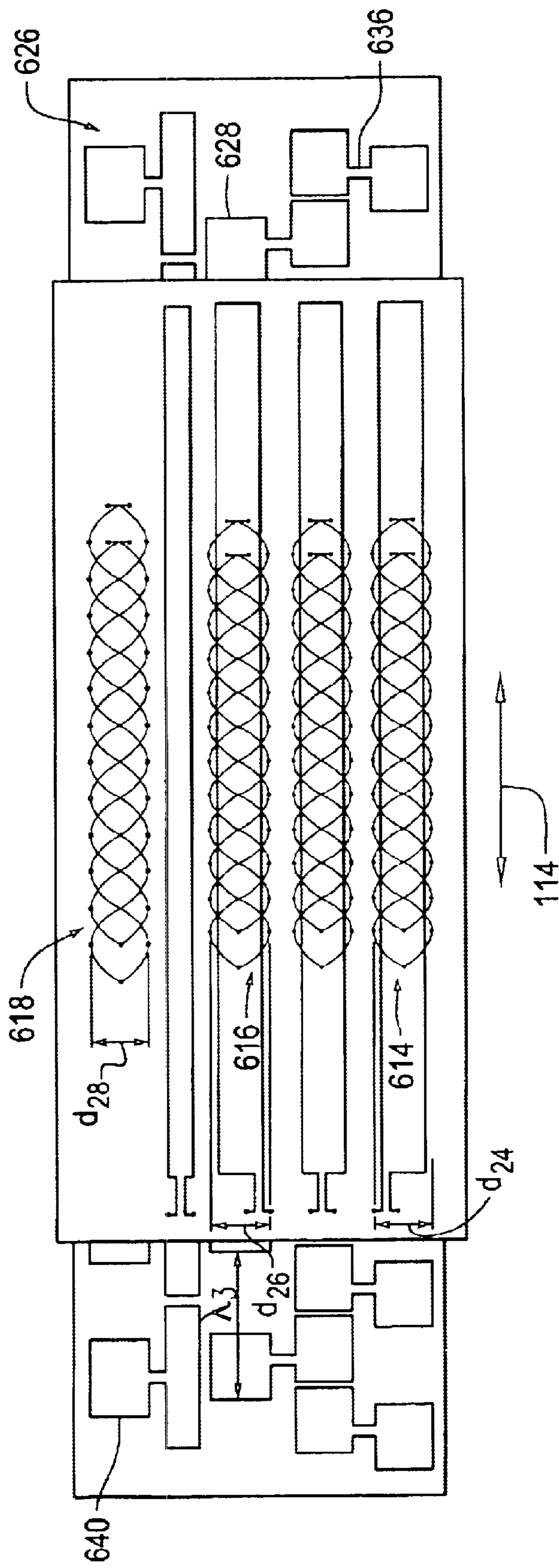


Fig. 9
PRIOR ART

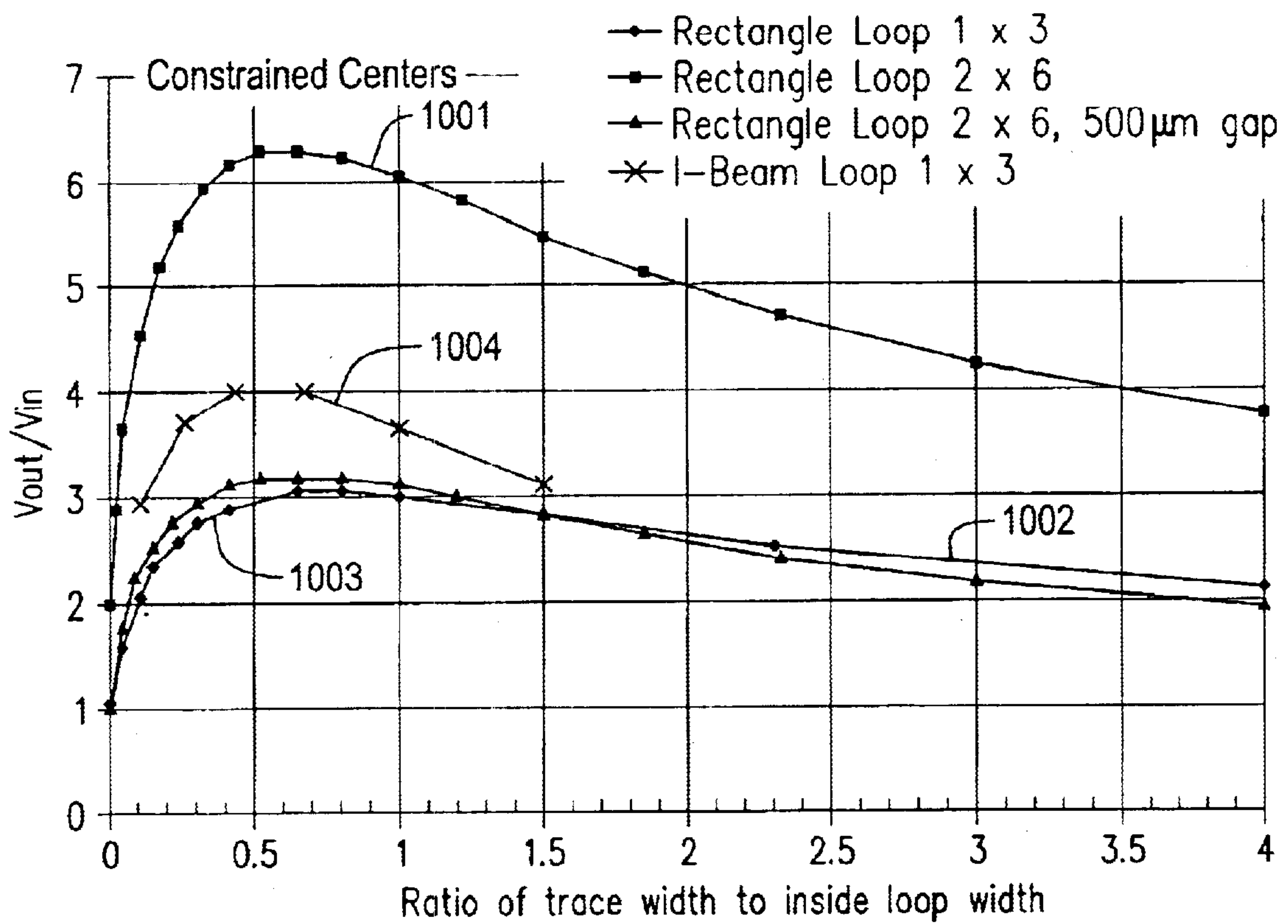


Fig. 10

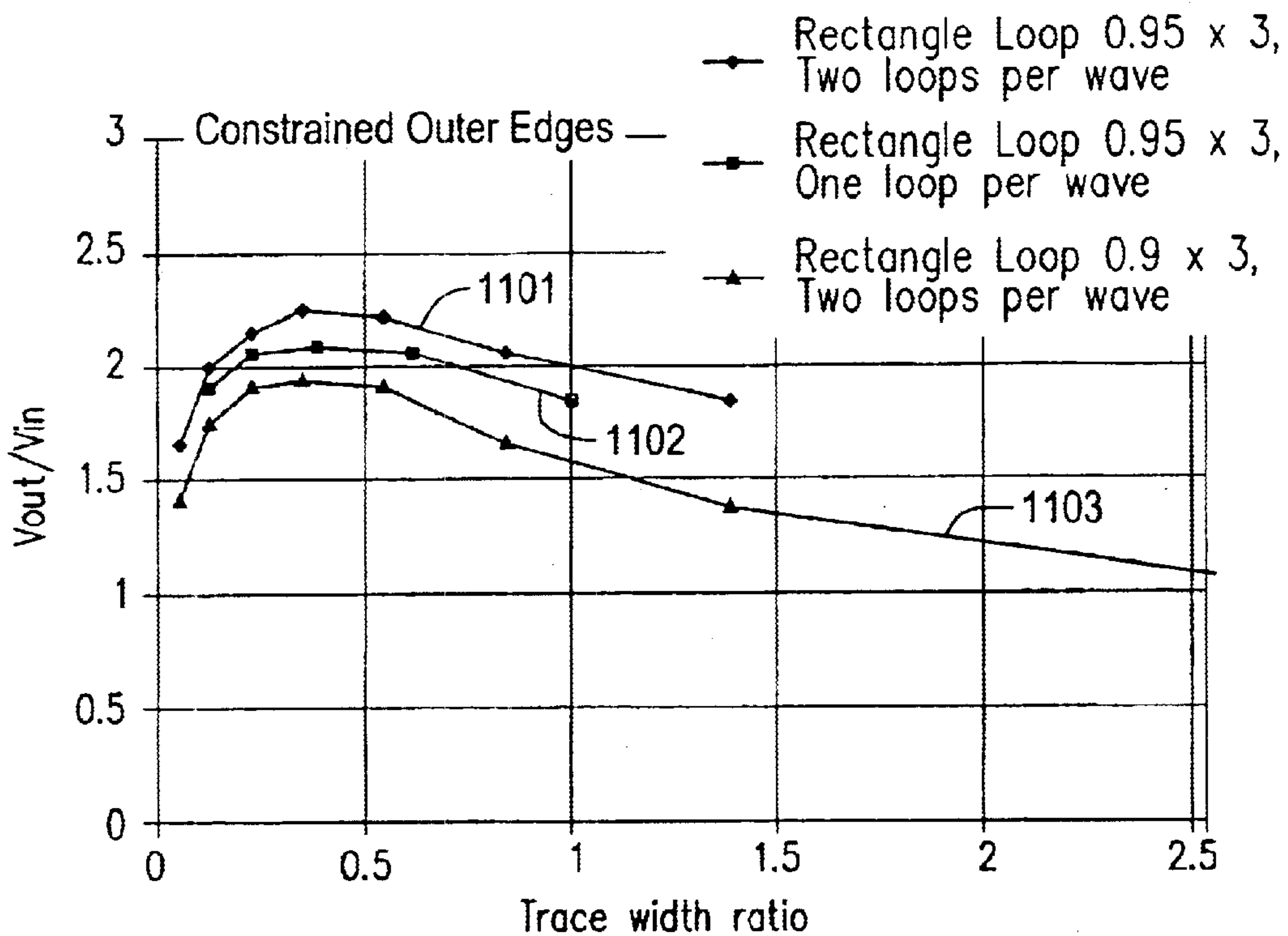


Fig. 11

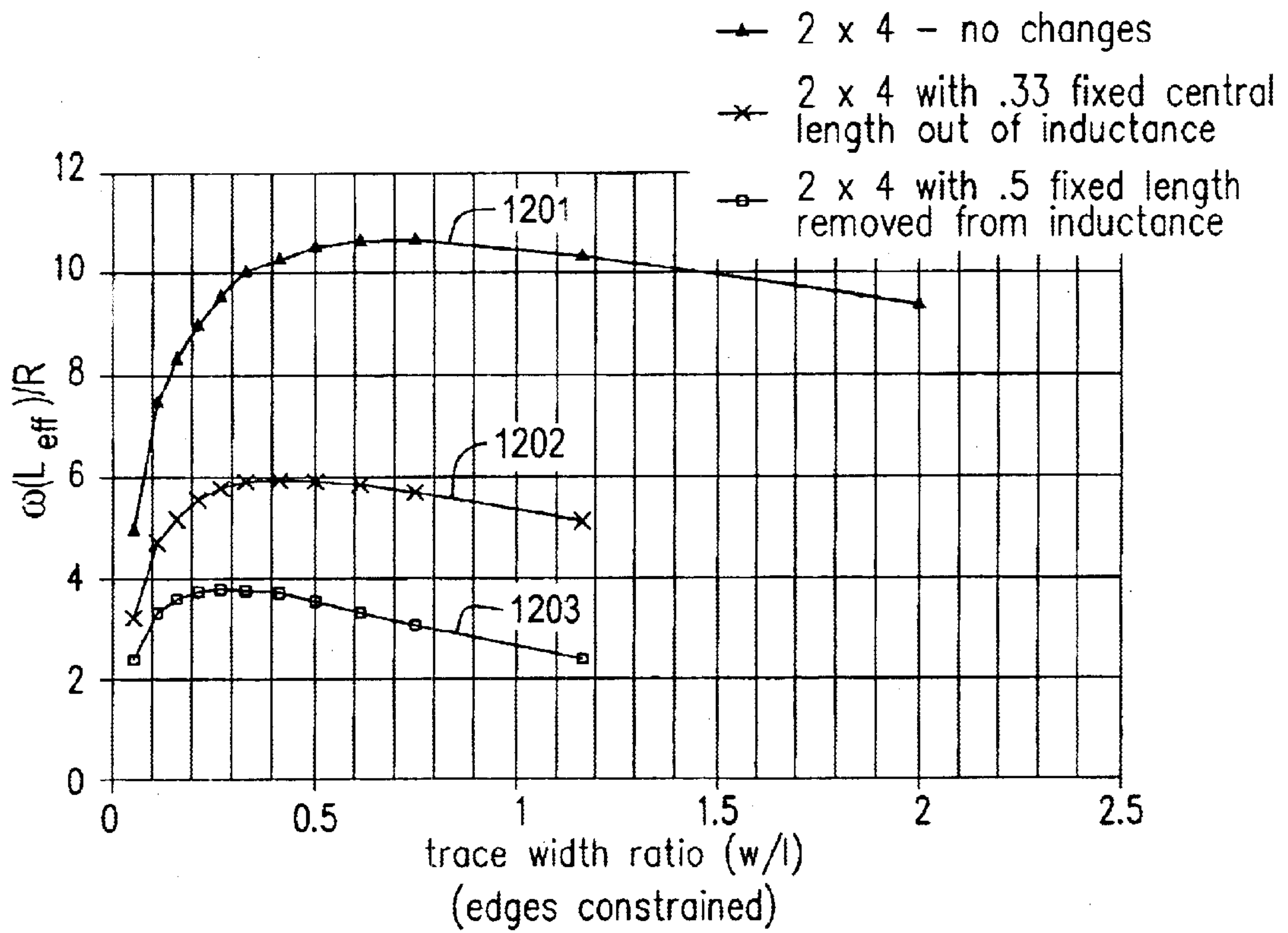
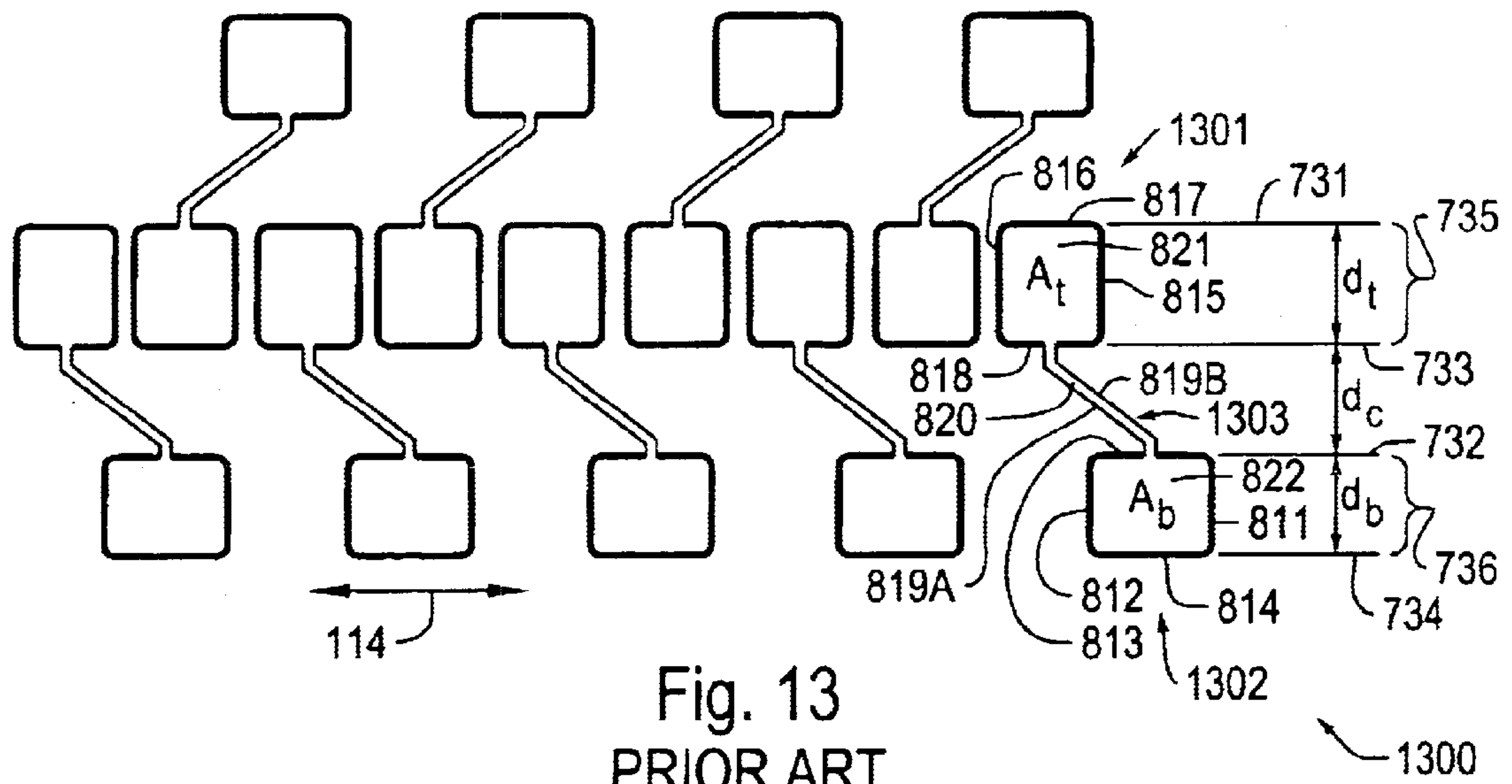


Fig. 12



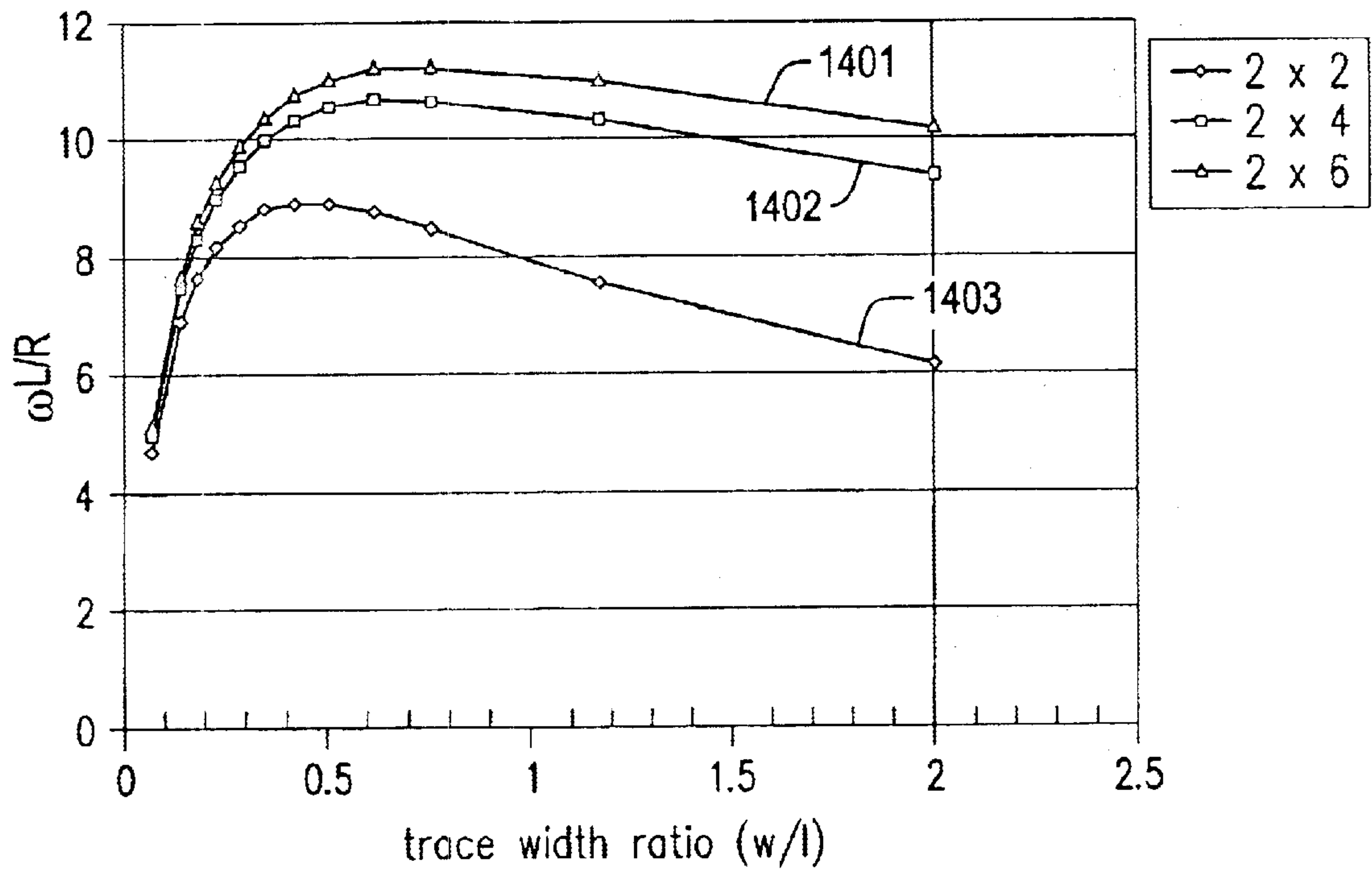


Fig. 14

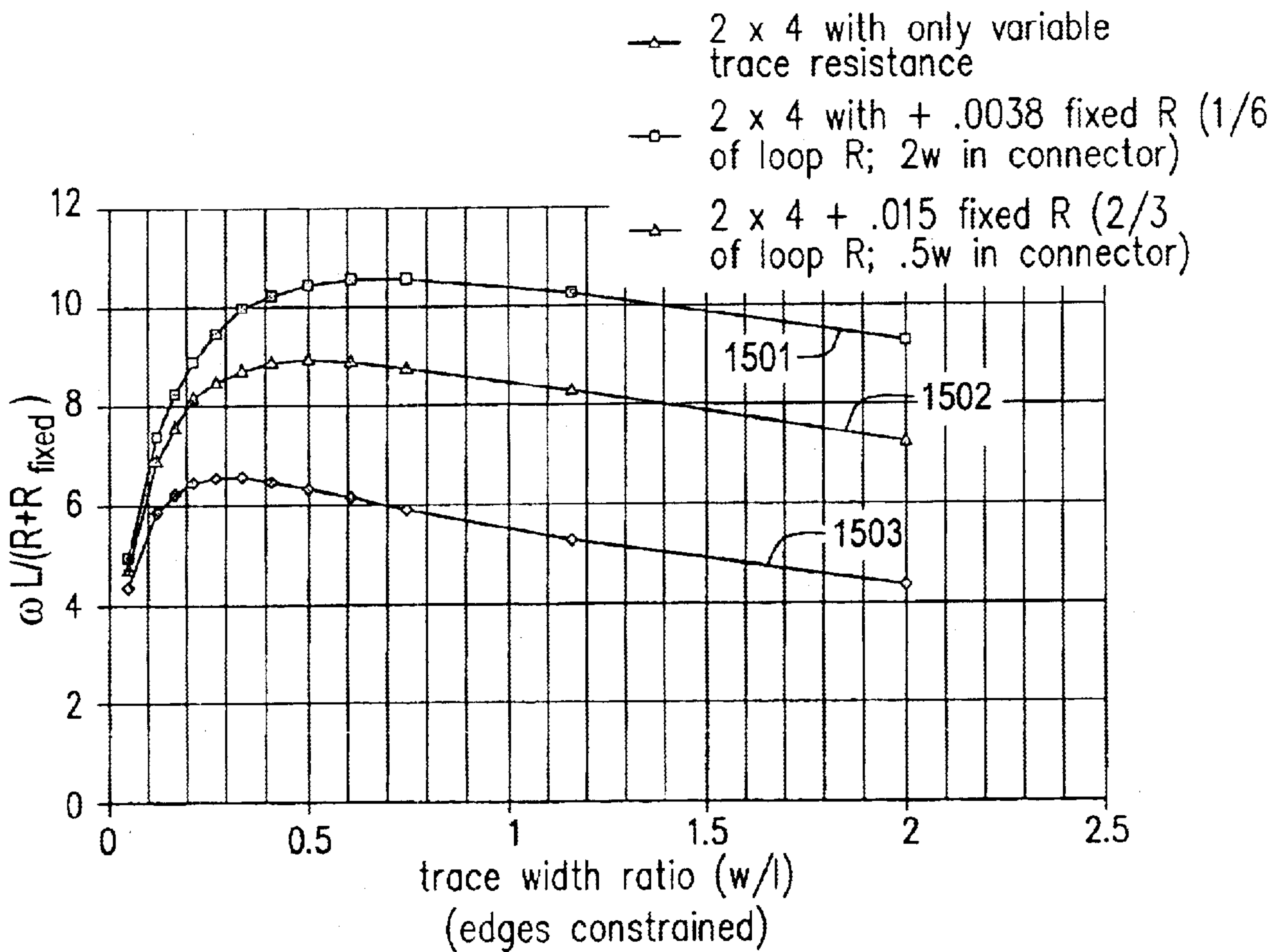


Fig. 15

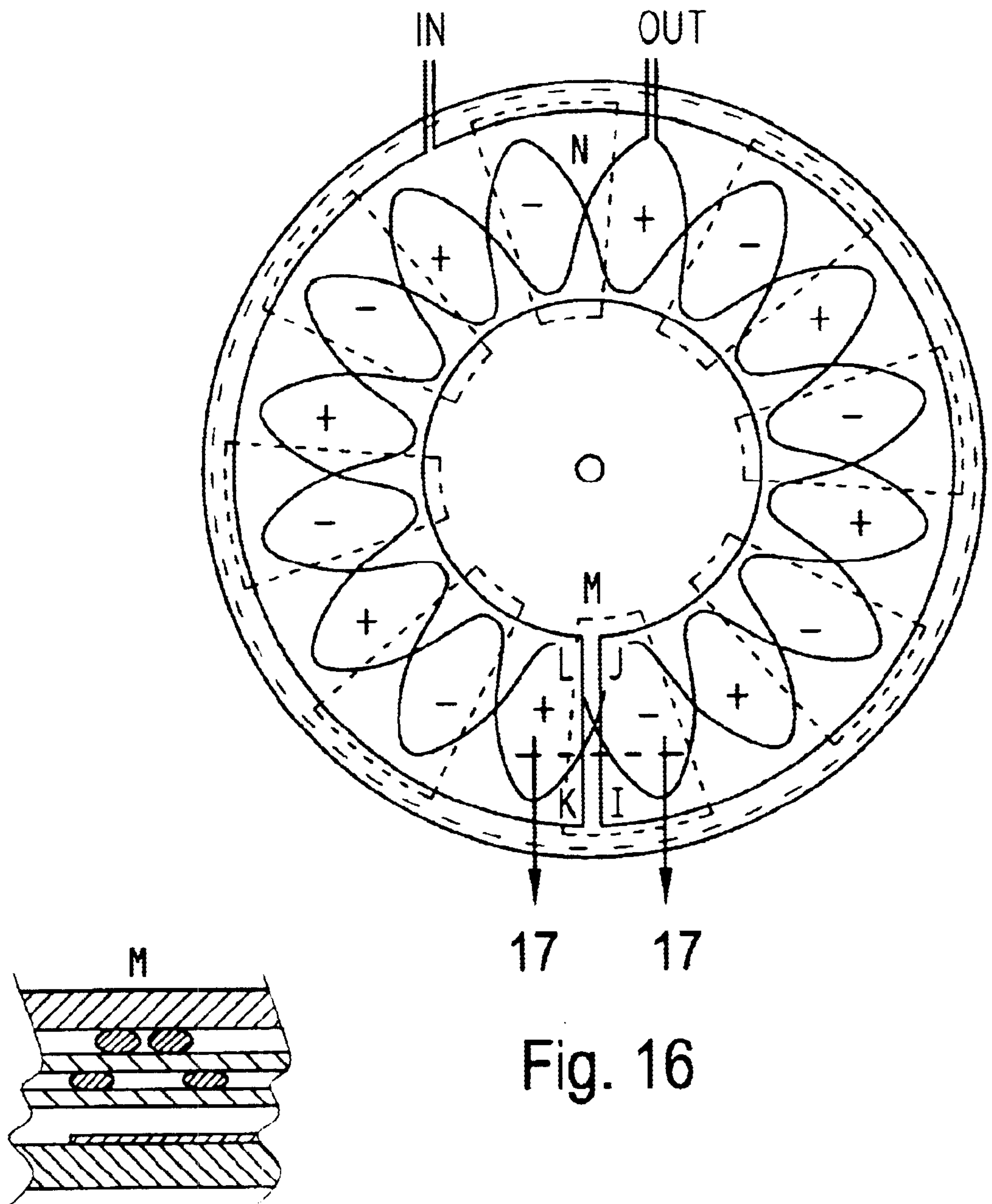


Fig. 16

Fig. 17

INDUCED CURRENT POSITION TRANSDUCERS HAVING IMPROVED SCALE LOOP STRUCTURES

BACKGROUND OF THE INVENTION

1. Field of Invention

This invention relates to induced current linear and rotary position transducers.

2. Description of Related Art

Various induced current position transducers are known. U.S. Pat. No. 5,973,494, incorporated herein by reference in its entirety, discloses an electronic caliper using an induced current position transducer. U.S. Pat. No. 6,005,387, incorporated herein by reference in its entirety, discloses various reduced-offset high accuracy induced current position transducers and associated signal processing techniques. U.S. application Ser. No. 09/421,497, now U.S. Pat. No. 6,400,138, incorporated herein by reference in its entirety, discloses various reduced-offset high accuracy induced current absolute position transducers and associated signal processing techniques.

A reduced-offset-type induced current position transducer generally includes a transmitter winding, a corresponding receiver winding and a signal generating and processing circuit on a readhead. Reduced-offset-type induced current position transducers are often configured so that the transmitter winding and the corresponding receiver winding occupy separate regions on the readhead. The transmitter winding and the corresponding receiver winding are spaced apart in a direction transverse to the measuring axis of the position transducer. The transducer also includes a scale having at least one scale loop. The transmitter winding is inductively coupled to a first portion of the scale loop and a second portion of the scale loop is, in turn, inductively coupled to the corresponding receiver winding.

When a time-varying signal originating from the signal generating and processing circuit passes through the transmitter winding, a primary magnetic field is generated. The transmitter winding is inductively coupled to the first portions of the scale loops by the primary magnetic field. The second portions of the scale loops generate secondary magnetic fields. The receiver winding is inductively coupled to the second portions of the scale loops by the secondary magnetic fields.

At least one of the transmitter winding or the receiver winding is formed in a periodic pattern, such as a sinusoidal pattern, having dimensions corresponding to the coupling loops. Various winding configurations are known in the art to reduce the extraneous inductive coupling in the device. The receiver windings inductively couple with the second loop portions of the scale loops in differing degrees, depending on the position of the scale relative to the readhead.

U.S. Pat. No. 6,011,389, incorporated herein by reference in its entirety, discloses an incremental induced current position transducer. U.S. Pat. Nos. 5,804,963, 4,853,684 and 6,259,249 disclose various other types of induced current position transducers. The '389, '963, '684 and '249 patents include scale configurations wherein periodically arranged scale elements, in some embodiments, comprise conductive loops. However, these patents include no teaching directed toward the size of the conductors comprising the conductive scale loops.

Furthermore, the conductor sizes represented in the drawings are inconsistent and/or artifacts of the illustration

process. Furthermore, the transmitter and receiver windings of the aforementioned patents are either not spaced apart in a direction transverse to the measuring axis of their respective induced current position transducers, or their underlying operating principle is otherwise significantly different from that associated with the present invention. For at least these reasons, the '389, '963, '684 and '249 patents are not instructive regarding scale loop designs according to this invention.

It is desirable for the position measurements obtained with reduced-offset-type induced current position transducers to have improved accuracy and resolution relative to the accuracy and resolution that are possible with known devices.

SUMMARY OF THE INVENTION

The accuracy and resolution of measurements taken with reduced offset-type induced position transducers are generally related to the signal strength provided by the transducer and the related signal-to-noise ratio of the overall position transducer signal processing. The signal strength is, in turn, related to the efficiency of the scale loops in inductively coupling to the transmitter and receiver windings of the reduced-offset-type induced current position transducer. Therefore, the coupling efficiency of the scale loops is an important factor in such transducer designs.

The resolution of measurements taken with reduced-offset-type induced current position transducers is improved when the spatial period or wavelength of the spatially varying magnetic field created by the scale loops is short, and when the signal measured by the receiver has a high signal-to-noise ratio. However, as the spatial period or wavelength of the magnetic field created by the scale loops is shortened by reducing the dimensions of the scale loops along the measuring axis, the signal provided by the scale loops is generally weaker at a given operating distance away from the scale loops. Further, fabricating the scale generally becomes more expensive as the dimensions of the scale loops are reduced.

Accordingly, there is a need for improved scale loop designs that help to improve performance and reduce fabrication costs of induced current position transducers.

The signal-to-noise ratio of the signal produced by the scale loops in a reduced-offset-type induced current position transducer depends significantly on the efficiency of the transfer of energy through the scale loops. The efficiency of the transfer of energy through the scale loops generally improves by decreasing the resistance and increasing the inherent inductance of the scale loops. These factors can be affected by manipulating the layout of the scale loops and the cross-sectional dimensions of the scale traces that individually form each of the scale loops.

However, scale loop design constraints are imposed by factors such as the desired scale wavelength and the desired overall dimensions of the scale and the readhead of the reduced offset-type induced position transducer. In particular, when a desired design constrains the distance spanned by a scale loop along the measuring axis, a balance must be achieved between the width of the scale trace, which is representative of the resistance, and the interior area of the scale loop, which is representative of the inherent inductance. Thus, an optimum scale loop design must consider the relationship between these parameters, as well as other practical fabrication considerations.

The resistance of a scale loop, is dependent on the geometry of the scale trace from which the scale loop is

formed. In particular, the resistance of the scale loop is dependent on the thickness and width of the scale trace, as well as its length. Additionally, the effective resistance of an operating scale loop also depends on the skin depth of the scale trace. The skin depth, in turn, depends on the material from which the scale trace is formed, and the operating frequency of the reduced offset-type inductive position transducer.

The inherent inductance of a scale loop depends primarily on the interior area of the scale loop. In particular, as the interior area of a scale loop is reduced, the inherent inductance of the scale loop is also reduced. As previously discussed, when the distance spanned by a scale loop along the measuring axis is constrained by other design imperatives, the interior area, and thus the inherent inductance, of a scale loop necessarily decreases as the width of the scale trace. Thus, to improve the related performance of the scale loops in a reduced offset-type induced current position transducer, the width of the scale trace forming the scale loop should be chosen to balance the need to minimize the resistance against the need to maintain a high inherent inductance.

Accordingly, this invention provides efficient scale loops that provide increased signal strength and improved resolution and accuracy of measurements, when employed in reduced offset-type induced current position transducers.

This invention separately provides scale loops of reduced-offset-type induced current position transducers, having reduced electrical resistance.

This invention separately provides scale loops of reduced-offset-type induced current position transducers, having improved inherent inductance in relation to their resistance.

Scale loops for reduced-offset induced current position transducers are provided which allow high resolution position measurements to be made. The scale loops designed according to this invention include a scale trace formed of an electrically conductive material arranged in a loop that is continuous and electrically isolated from adjacent scale loops. The shape of the scale loop is not limited, but rather is determined by the particular configuration of the reduced offset-type induced current position transducer in which the scale loop will be employed.

These and other features and advantages of this invention are described in, or are apparent from, the following detailed description of various exemplary embodiments of the systems and methods according to this invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Various exemplary embodiments of this invention will be described in detail, with reference to the following figures, wherein:

FIG. 1 is a known reduced-offset scale for use in an induced current position transducer;

FIG. 2 is a known reduced-offset-type induced current position transducer;

FIG. 3 is a schematic diagram of a simplified equivalent circuit of an induced current position transducer;

FIG. 4 is a graph showing the relationship between signal gain and the scale impedance dependent portion of the received signal of an induced current position transducer;

FIG. 5 is a graph showing values of signal gain in an induced current position transducer as a function of scale trace thickness;

FIG. 6 is a graph showing signal gain as a function of the ratio of trace width to interior length, of a scale loop situated

on a scale so that the scale trace centers are at a constrained spacing along the measuring axis of an induced current position transducer at various operating frequencies;

FIG. 7 illustrates a first exemplary embodiment of a scale loop according to this invention;

FIG. 8 illustrates a second exemplary embodiment of a scale loop according to this invention;

FIG. 9 is a known reduced-offset-type induced current absolute position transducer;

FIG. 10 is a graph showing signal gain as a function of the ratio of trace width to interior length of a scale loop situated on a scale so that the scale traces are at a constrained spacing along the measuring axis, for various scale loops in an induced current position transducer operating at 10 MHz;

FIG. 11 is a graph showing signal gain as a function of the ratio of trace width to the interior length of a rectangular scale loop situated on a scale so that the overall loop size is constrained, for various size and scale configurations in an induced current position transducer operating at 10 MHz;

FIG. 12 is a graph showing a quantity related to the signal provided by rectangular loops having various effective coupling areas as a function of the ratio of trace width to the interior length of the loop situated on a scale so that the overall loop size is constrained;

FIG. 13 is a drawing of the scale loops of a known reduced-offset-type induced current absolute position transducer;

FIG. 14 is a graph showing a quantity related to the signal provided by various rectangular loops as a function of the ratio of trace width to interior length of the loop situated on a scale so that the overall loop size is constrained;

FIG. 15 is a graph showing a quantity related to the signal provided by a rectangular loops in series with various fixed resistances as a function of the ratio of trace width to the interior length of the loop situated on a scale so that the overall loop size is constrained; and

FIG. 16 is an induced-current transducer with a measurement axis extending in a circular path; and

FIG. 17 is a cross-section of the induced-current transducer of FIG. 16.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

FIG. 1 illustrates an exemplary embodiment of a reduced-offset scale. As shown in FIG. 1, the reduced-offset scale 210 includes a first plurality of closed-loop scale loops 212 interleaved with a second plurality of closed-loop scale loops 216.

Each of the first plurality of scale loops 212 includes a first loop portion 213 and a second loop portion 214 connected by a pair of connecting conductors 215. Similarly, each of the second plurality of scale loops 216 includes a first loop portion 217 and a second loop portion 218 connected by a pair of connecting conductors 219.

In the first plurality of scale loops 212, the first loop portions 213 are arranged along one lateral edge of the scale 210 and are arrayed along a measuring axis 114. The second loop portions 214 are arranged along the center of the scale 210 and are arrayed along the measuring axis 114. The connecting conductors 215 extend perpendicularly to the measuring axis 114 to connect the first loop portions 213 to the second loop portions 214.

Similarly, in the second plurality of scale loops 216, the first loop portions 217 are arranged along a second lateral

edge of the scale **210** and arrayed along the measuring axis **114**. The second loop portions **218** are arranged along the center of the scale **210** along the measuring axis, interleaved with the second loop portions **214** of scale loops **212**. The connecting conductors **219** extend generally perpendicularly to the measuring axis **114** to connect the first loop portions **217** to the second loop portions **218**.

FIG. 2 illustrates an exemplary embodiment of an induced current position transducer **200** that includes the reduced-offset scale **210**. As shown in FIG. 2, a readhead **220** of the transducer **200** includes a transmitter winding **222** having a first transmitter winding portion **223A** and a second transmitter winding portion **223B**. As shown in FIG. 2, the first transmitter winding portion **223A** is provided at a first lateral edge of the readhead **220**, while the second transmitter winding portion **223B** is provided at the other lateral edge of the readhead **220**. Each of the first and second transmitter winding portions **223A** and **223B** have the same long dimension extending along the measuring axis **114**. Furthermore, each of the first and second transmitter winding portions **223A** and **223B** have a short dimension that extends in a direction perpendicular to the measuring axis **114** a distance d_1 .

The terminals **222A** and **222B** of the transmitter winding **222** are connected to the transmitter drive signal generator **150**. The transmitter drive signal generator **150** outputs a time-varying drive signal to the transmitter winding terminal **222A**. Thus, a time-varying current flows through the transmitter winding **222** from the transmitter winding terminal **222A** to the transmitter terminal **222B**, as indicated in FIG. 2.

In response, the first transmitter winding portion **223A** generates a primary magnetic field that rises up out of the plane of FIG. 2 inside the first transmitter winding portion **223A** and descends into the plane of FIG. 2 outside the loop formed by the first transmitter winding portion **223A**. In contrast, the second transmitter winding portion **223B** generates a primary magnetic field that rises out of the plane of FIG. 2 outside the loop formed by the second transmitter winding portion **223B** and descends into the plane of FIG. 2 inside the loop formed by the second transmitter winding portion **223B**. In response, a current is induced in the scale loops **212** and **216** that counteracts the change of magnetic field.

Thus, the induced current in each of the scale loop sections **213** and **217** flows in a direction opposite to the current flowing in the respective adjacent portions of the transmitter loops **223A** and **223B**. As shown in FIG. 2, adjacent ones of the second loop portions **214** and **218** in the center section of the scale have loop currents having opposite polarities. Thus, a secondary magnetic field is created having field portions of opposite polarity periodically distributed along the center section of the scale. The wavelength λ of the periodic secondary magnetic field is equal to the distance between successive second loop portions **214** (or **218**).

The readhead **220** also includes first and second receiver windings **224** and **226**. The first and second receiver windings **224** and **226** are each formed by a plurality of sinusoidally shaped loop segments **228** and **229** formed on opposite sides of an insulating layer of the printed circuit board forming the readhead **220**. The loop segments **228** and **229** are linked through feed-throughs **230** to form alternating positive polarity loops **232** and negative polarity loops **234** in each of the first and second receiver windings **222** and **226**. The receiver windings **224** and **226** are positioned in the

center of the readhead **220** between the first and second transmitter portions **223A** and **223B**. Each of the first and second receiver windings **224** and **226** extends in the direction perpendicular to the measuring axis a distance d_2 . The first and second receiver windings **224** and **226** are spaced equal distances d_3 from the inner portions of the first and second transmitter winding portions **223A** and **223B**.

The loops **232** and **234** in each of the first and second receiver windings **224** and **226** have a width along the measuring axis **114** equal to $\lambda/2$. Thus, each pair of adjacent loops **232** and **234** has a width equal to λ . Furthermore, the first and second loop segments **228** and **229** go through a full sinusoidal cycle in each pair of adjacent loops **232** and **234**. Thus, λ corresponds to the sinusoidal wavelength, that is, the spatial period of the first and second receiver windings **224** and **226**. Furthermore, the receiver winding **226** is offset by $\lambda/4$ from the first receiver winding **224** along the measuring axis **114**. That is, the first and second receiver windings **224** and **226** are in quadrature.

The changing drive signal from the transmitter driver generator **150** is applied to the transmitter winding **222** such that current flows in the transmitter winding **222** from a first terminal **222A**, through the transmitter winding **222** and out through a second terminal **222B**. Thus, the magnetic field generated by the transmitter winding **222** descends into the plane of FIG. 1 within the transmitter winding **222** and rises up out of the plane of FIG. 1 outside the transmitter winding **222**. Accordingly, the changing magnetic field within the transmitter winding **222** generates an induced electromotive force (EMF) in each of the loops **232** and **234** formed in the receiver windings **224** and **226**.

The loops **232** and **234** have opposite winding directions. Thus, the EMF induced in the loops **232** has a polarity that is opposite to the polarity of the EMF induced in the loops **234**. The loops **232** and **234** enclose the same size areas and thus nominally the same amount of magnetic flux. Therefore, the absolute magnitude of the EMF generated in each of the loops **232** and **234** is nominally the same.

There are preferably equal numbers of loops **232** and **234** in each of the first and second receiver windings **224** and **226**. Ideally, the positive polarity EMF induced in the loops **232** is exactly offset by the negative polarity EMF induced in the loops **234**. Accordingly, the net nominal EMF on each of the first and second receiver windings **224** and **226** is zero and it is intended that no signal is output from the first and second receiver windings **224** and **226** as a result solely of the direct coupling from the transmitter winding **222** to the receiver windings **224** and **226**.

Each of the first plurality of scale loops **212** is arranged at a pitch equal to a wavelength λ of the first and second receiver windings **224** and **226**. Furthermore, the first loop portions **213** each extends a distance along the measuring axis **114** which is as close as possible to the wavelength λ while still providing the insulating spaces **201** between adjacent ones of the first loop portions **213**. In addition, the first loop portions **213** extend the distance d_1 in the direction perpendicular to the measuring axis **114**.

Similarly, each of the second plurality of scale loops **216** is also arranged at a pitch equal to the wavelength λ . The first loop portions **217** also extend as close as possible to each other along the measuring axis to the wavelength λ while providing the spaces **201** between adjacent ones of the first loop portions **217**. The first loop portions **217** also extend the distance d_1 in the direction perpendicular to the measuring axis **114**.

The second loop portions **214** and **218** of the first and second pluralities of scale loops **212** and **216** are also

arranged at a pitch equal to the wavelength λ . However, each of the second loop portions **214** and **218** extends along the measuring axis as close as possible to only one-half the wavelength λ . An insulating space **202** is provided between each adjacent pair of second loop portions **214** and **218** of the first and second pluralities of scale loops **212** and **216**, as shown in FIG. 2. Thus, the second loop portions **214** and **218** of the first and second pluralities of scale loops **212** and **216** are interleaved along the length of the scale **210**. Finally, each of the second loop portions **214** and **218** extends the distance d_2 in the direction perpendicular to the measuring axis **114**.

As shown in FIG. 2, the second loop portions **214** and **218** are spaced the distance d_3 from the corresponding first loop portions **213** and **217**. Accordingly, when the read head **220** is placed in proximity to the scale **210**, as shown in FIG. 2, the first transmitter winding portion **223A** aligns with the first loop portions **213** of the first plurality of scale loops **212**. Similarly, the second transmitter winding portion **223B** aligns with the first loop portions **217** of the second plurality of scale loops **216**. Finally, the first and second receiver windings **224** and **226** align with the second loop portions **214** and **218** of the first and second scale loops **212** and **216**.

In operation, a time-varying drive signal is output by the transmitter drive signal generator **150** to the transmitter winding terminal **222A**. Thus, the first transmitter winding portion **223A** generates a first changing magnetic field having a first direction while the second transmitter winding portion **223B** generates a second magnetic field in a second direction that is opposite to the first direction. This second magnetic field has a field strength that is equal to a field strength of the first magnetic field generated by the first transmitter winding portion **223A**.

Each of the first plurality of scale loops **212** is inductively coupled to the first transmitter winding portion **223A** by the first magnetic field generated by the first transmitter winding portion **223A**. Thus, an induced current flows clockwise through each of the first plurality of scale loops **212**. At the same time, the second plurality of scale loops **216** is inductively coupled to the second transmitter winding portion **223B** by the second magnetic field generated by the second transmitter winding portion **223B**. This induces a counterclockwise current to flow in each of the second plurality of scale loops **216**. That is, the currents through the second portions **214** and **218** of the scale loops **212** and **216** flow in opposite directions.

The clockwise flowing current in each of the second portions **214** of the first scale loops **212** generates a third magnetic field that descends into the plane of FIG. 2 within the second portions **214**. In contrast, the counterclockwise flowing currents in the second loop portions **218** of the second scale loops **216** generate a fourth magnetic field that rises out of the plane of FIG. 2 within the second loop portions **218** of the second scale loops **216**. Thus, a net alternating magnetic field is formed along the measuring axis **114**. This net alternating magnetic field has a wavelength which is equal to the wavelength λ of the first and second receiver windings **224** and **226**.

Accordingly, when the positive polarity loops **232** of the first receiver winding **224** are aligned with either the second loop portions **214** or **218**, the negative polarity loops **234** of the first receiver winding **224** are aligned with the other of the second loop portions **214** or **218**. This is also true when the positive polarity loops **232** and the negative polarity loops **234** of the second receiver winding **226** are aligned with the second loop portions **214** and **218**. Because the

alternating magnetic field generated by the second loop portions **214** and **218** is spatially modulated at the same wavelength as the spatial modulation of the first and second receiver windings **214** and **216**, the EMF generated in each of the positive and negative polarity loops **232** and **234** when aligned with the second loop portions **214** is equal and opposite to the EMF generated when they are aligned with the second loop portions **218**.

Thus, the net output of the positive polarity loops **232**, as the readhead **220** moves relative to the scale **210** is a sinusoidal function of the position "x" of the read-head along the scale and the offset component of the output signal due to extraneous scale is nominally zero. Similarly, the net output from the negative polarity loops **234**, as the readhead **220** moves relative to the scale **210**, is also a sinusoidal function of the position "x" of the readhead along the scale and the offset component of the output signal due to extraneous scale is nominally zero. The EMF contributions from the positive polarity loops **232** and the negative polarity loops **234** are in phase.

Finally, the first and second receiver windings **224** and **226** are in quadrature. Thus, the output signal generated by the first receiver winding **224** as a function of x and output to the receiver signal processing circuit **140** is 90° out of phase with the signal output by the second receiver winding **226** as a function of x to the receiver signal processing circuit **140**.

The receiver signal processing circuit **140** inputs and samples the output signals from the first and second receiver windings **224** and **226**, converts these signals to digital values and outputs them to the control unit **160**. The control unit **160** processes these digitized output signals to determine the relative position x between the readhead **220** and the scale **210** within a wavelength λ .

Based on the nature of the quadrature output from the first and second receiver windings **224** and **226**, the control unit **160** is able to determine the direction of relative motion between the readhead **220** and the scale **210**. The control unit **160** counts the number of partial or full "incremental" wavelengths λ traversed, by signal processing methods well-known to those skilled in the art and disclosed herein and in the incorporated references. The control unit **160** uses that number and the relative position within a wavelength λ to output the relative position between the readhead **220** and the scale **210** from a set origin.

The control unit **160** also outputs control signals to the transmitter drive signal generator **150** to generate the time-varying transmitter drive signal. It should be appreciated that any of the signal generating and processing circuits shown in the incorporated references can be used to implement the receiver signal processing circuit **140**, the transmitter drive signal generator **150** and the control unit **160**. Thus, these circuits will not be described in further detail herein.

As discussed above, high resolution position measurements are desirable, and can be achieved by shortening the spatial period of the time-varying magnetic field created by a scale of an induced current position transducer and increasing the signal-to-noise ratio. The signal-to-noise ratio depends significantly on the efficiency of the transfer of energy through the scale loops **212** formed on the scale **210**. FIG. 3 illustrates a simplified equivalent circuit for a typical reduced-offset-type induced current position transducer, such as the reduced-offset transducer **200** shown in FIG. 2. The circuit includes a transmitter loop **310**, several scale loops **320**, and a receiver loop **330**.

The periodic nature of the position transducer is illustrated by the multiple scale loops **320**, which approximate the scale loops found in a typical induced current position transducer, such as the positive polarity loops **212** and negative polarity loops **214** of the position transducer **200** in FIG. 2, which are spaced periodically in a pattern having a wavelength λ . It should be appreciated that, in a typical induced current position transducer, both the transmitter and receiver loops couple to a plurality of scale loops simultaneously. However, it should be understood that a configuration of a scale loop that maximizes the signal for that particular scale loop will generally maximize the combined signal from multiple scale loops if the configuration is repeated. Accordingly, the following discussion focuses on improving the signal provided by a single scale loop, for clarity.

As shown in FIG. 3, the transmitter loop **310** has an inherent inductance L_T and a resistance R_T . The inherent inductance L_T represents the inductance of a portion of the transmitter loop **310** coupled to the scale loop **320**. For the transmitter loop of a typical induced current position transducer, the total inductance is approximately 10–100 nH and the resistance R_T is typically in the milliohm range. However, in general, factors governing these transmitter parameters are not important to understanding the present invention, and are not discussed further herein. Similarly, the receiver loop **330** has an inherent inductance L_R and a resistance R_R . The inherent inductance L_R represents the inductance of the portion of the receiver loop **300** coupled to the scale loop **320**. For the receiver loop of a typical induced current position transducer, the total inductance is approximately 10–1000 nH and the resistance R_R is typically in the 1–100 milliohm range. However, in general, factors governing these receiver parameters are not relevant to the present invention and are not discussed further herein. A receiver load resistance R_L is shown coupled across the terminals of the receiver winding **330**. The receiver load resistance R_L is part of the measurement circuit that measures V_{out} ; and is typically significantly greater than other impedances in the circuit. In various exemplary embodiments, the receiver load resistance R_L is in the range of 50–500 ohms.

The scale loops **320** each have inherent inductances L_{S1} and L_{S2} and a resistance R_S . In practice, R_S is reduced to the greatest extent possible under practical fabrication constraints. For example, R_S may be in the range of 0.01–1 milliohm. The inherent inductance L_{S1} is the inductance of a portion of the scale loop **320** coupled to the transmitter winding **310** and the inherent inductance L_{S2} is the inductance of a portion of the scale loop **320** coupled to the receiver winding **330**. In practice, it is often desirable that L_{S1} and L_{S2} are approximately equal in order to maximize the transfer of energy from the transmitter winding **310** to the receiver winding **330**.

Further, in known induced current position transducers, such as that shown in FIG. 9 and described in the incorporated '497 application, in scale loops having multiple portions, each scale loop portion can be coupled to either a transmitter winding or a receiver winding at various times during operation to produce two signals having two different spatial periods from the same scale track. Thus, an approximately symmetrical scale loop is appropriate for operation in such inductive position transducer configurations. Thus, while scale loops having asymmetrical inductance with the transmitter and receiver loops are encompassed by this invention, the following description is simplified by assuming that L_{S1} equals L_{S2} and L_S equals either L_{S1} or L_{S2} .

As shown in FIG. 3, a first parameter k_T is a factor indicating the strength of the inductive coupling between the transmitter winding and a scale loop, and may be considered a constant, independent of position, when a scale loop is operationally positioned relative to the transmitter winding. A second parameter k_R is a factor indicating the strength of the inductive coupling between the receiver winding and a scale loop, and may be considered a periodic function of position when a scale loop is operationally positioned relative to the periodic receiver winding.

When it is assumed that the resistance R_L is large compared to other impedances and that one resistance R_T is small compared to other impedances, the signal gain of the general circuit of FIG. 3 is given by:

$$\frac{V_{out}}{V_{in}} = k_T k_R \sqrt{\frac{L_R L_{S1}}{L_T L_{S2}}} \frac{1}{\sqrt{\left(\frac{R_S}{\omega L_{S2}}\right)^2 + \left(\frac{L_{S1}}{L_{S2}}(1 - k_T^2) + 1\right)^2}} \quad (1)$$

where:

V_{in} is the voltage generated at the transmitter;

V_{out} is the voltage detected at the receiver;

k_T is a factor indicating the strength of the inductive coupling between the transmitter winding and a scale loop;

k_R is a factor indicating the strength of the inductive coupling between a scale loop and the receiver winding;

L_R is the inductance of the portion of the receiver loop coupled to a scale loop;

L_T is the inductance of the portion of the transmitter loop coupled to a scale loop;

R_S is the resistance of a scale loop;

ω is the operating frequency of the induced current position transducer;

L_{S1} is the inherent inductance of the portion of the scale loop coupled to the transmitter; and

L_{S2} is the inherent inductance of the portion of the scale loop coupled to the receiver. Assuming that L_{S1} and L_{S2} are equal interchangeably represented by L_S , the signal gain of the general circuit of FIG. 3 is given by:

$$\frac{V_{out}}{V_{in}} = k_T k_R \sqrt{\frac{L_R}{L_T}} \frac{1}{\sqrt{\left(\frac{R_S}{\omega L_S}\right)^2 + (2 - k_T^2)^2}} \quad (2)$$

FIG. 4 is a graph illustrating the relationship between the signal gain and the scale impedance $(R_S^2/(\omega L_S)^2)$, as described in Equation 2. Upon inspection of Equation 2 and observation of FIG. 4, it should be appreciated that, with other factors held constant, the signal gain V_{out}/V_{in} will increase as the quantity $(R_S^2/(\omega L_S)^2)$ decreases. Accordingly, to obtain an increase in the signal gain in an induced current position transducer, in various exemplary embodiments of the scale loops according to this invention, the resistance of the scale loop should be reduced without decreasing the inductance of the scale loop, or at least the resistance should be reduced to a greater extent than the inductance of the scale loop.

FIG. 4 shows, for example, that to increase the signal gain it is very useful to reduce R_S^2 below $(\omega L_S)^2$. FIG. 4 also shows that there is little additional improvement in signal gain when R_S^2 is reduced below $0.1 * (\omega L_S)^2$. More

generally, the information of FIG. 4 is useful for choosing a particular relation between the resistance R_s and the inductance L_s at a particular operating frequency ω .

However, as previously discussed, when the distance spanned by a scale loop along the measuring axis of an induced current position transducer is constrained by various design considerations, the interior area, and thus the inherent inductance, of a scale loop must decrease as the width of the scale trace increases to reduce its resistance. Thus, with due consideration of various inductive position transducer design constraints, in various exemplary embodiments, the width of the scale trace is chosen to achieve an improved relationship between the resistance R_s and the inductance L_s of the scale loops of an induced current position transducer.

In various exemplary embodiments, relatively planar conductive scale traces are employed. For a relatively planar scale trace in a induced current position transducer operating at higher frequencies, it is generally known or believed that the current density is largest at the surface of the scale trace and that the magnitude of electromagnetic waves within the conductor decreases exponentially as the distance from the surface of the scale trace increases. Accordingly, at a given location within the conductor, the current density also decreases exponentially as the distance from the surface of the conductor increases.

The skin depth (δ) is a well-known measure of the distance from the surface of a conductor at which the current density is generally expected to decrease to $1/e$ of the value of the current density at the surface. The skin depth is defined as:

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} \quad (2)$$

where:

δ is the skin depth of the conductor at the operating frequency of the induced current position transducer;

σ is the conductivity of the conductor;

μ is the magnetic permeability of the material; and

ω describes the frequency of the oscillating wave.

In view of this relationship, at a DC frequency (i.e. $\omega=0$), the current density will be uniform across a relatively planar scale trace cross section and will be approximately proportional to the trace thickness. However, at higher frequencies, the majority of the current will be confined to a region approximately within a skin depth δ of the surface of the scale trace, regardless of the thickness of the scale trace. The effective resistance of a scale loop formed from such a scale trace will not decrease appreciably as the thickness of the scale trace increases beyond about 1 to 3 skin depths (i.e. $\delta-3\delta$). Thus, in various exemplary embodiments of the scale loops according to this invention, a conductive scale trace forming a scale loop according to this invention has a thickness of less than about 3 skin depths (3δ). In various other exemplary embodiments, a scale trace forming a scale loop according to this invention has a thickness of less than about 1 skin depth (δ).

Further, several other relationships are evident in view of Equation 3. When a scale trace has a thickness of less than the skin depth δ , the effective resistance of the scale trace will generally significantly increase with decreasing thickness of the scale trace. As previously discussed, as the effective resistance of the scale trace increases, the signal gain will generally decrease. Furthermore, the skin depth varies with the frequency of the electric field, such that, as the operating frequency increases, the skin depth δ decreases.

FIG. 5 is a graph showing values of the signal gain in an induced current position transducer as a function of the scale trace thickness. The graph in FIG. 5 indicates that when other factors affecting the resistance and inductance of a loop trace are held constant, a scale trace thickness of about 1 skin depth improves the signal gain at high operating frequencies to close to a maximum value. The graph further demonstrates that an increase in the scale trace thickness up to about 3 skin depths is useful for increasing the signal gain at an operating frequency of 1 MHz.

FIG. 5 also illustrates that induced current position transducers operating at higher operating frequencies, employing scale loops with scale trace thicknesses as small as about 0.3 skin depths allow approximately 80% of the maximum possible signal to be retained. Further, no signal improvement results from increasing the loop trace thickness beyond about 1 skin depth. The inventor believes that these unexpected results may be due to the particular arrangement of conductors in an induced current position transducer giving rise to high-frequency fields which are not readily modeled or understood according to the previously-discussed simple understanding.

When fabricating scale loop traces, for example by thin film techniques or conventional printed circuit techniques, it is generally more expensive and/or less accurate to fabricate thicker traces. Thus, in various exemplary embodiments of the scale loops according to this invention, the scale loop includes a scale trace having a thickness of less than about 1.0 skin depth. In various other exemplary embodiments, the scale loops of the instant invention include scale traces having a thickness of between about 0.3 skin depths and about 1.0 skin depths.

For example, at 10 MHz, a typical operating frequency for a reduced-offset-type induced current position transducer, the skin depth of copper, a typical conductive material used to form the scale loops, is about 0.02 mm. For the reasons described above, the amount of current in a copper trace will not change significantly if the trace has a thickness that exceeds the skin depth of copper at the operating frequency of the reduced-offset-type induced current position transducer. Based on the relationships described in FIG. 5, to improve the resistance of a scale loop, it is not very effective to form the scale trace at a thickness that is significantly greater than approximately the skin depth of the scale trace material in a reduced-offset-type induced current position transducer operating at 10 MHz. Thus, in various exemplary embodiments, in a reduced-offset-type induced current position transducer operating at 10 MHz a scale loop according to this invention is formed from a copper scale trace having a relatively planar rectangular cross section and a thickness of about 0.02 mm. In various other exemplary embodiments, the scale loop of this invention is formed from a copper scale trace having a thickness of between about 0.02 mm and about 0.006 mm.

As illustrated in FIG. 5, at higher operating frequencies, the effective resistance of a scale loop will not decrease appreciably as the thickness of the scale trace is increased beyond about 1 skin depth. In such a case, it is desirable to increase the width of the scale trace in order to further decrease the resistance of the scale trace, as described below.

As previously indicated, the distance spanned by a scale loop along the measuring axis is generally constrained according to various inducted current position transducer design considerations, such as a spatial period or wavelength of the transducer. Thus, as the width of a scale trace is increased to thereby decrease its resistance, the available interior area and the associated inherent inductance of the

scale loop will decrease accordingly. However, as discussed above, reduced mutual inductance between the transducer elements results in an undesirable reduction in signal gain. To address this undesirable effect, the inventors have discovered significant relationships between the width of a scale trace and the interior length along the measuring axis of the area enclosed by the scale loop, when the dimensions of the scale loop along the measuring axis are constrained by design requirements.

A known induced current position transducer that uses periodically arranged scale loops to couple transmitter and receiver windings which occupy separate regions on a readhead is commercially available in the digital Absolute Coolant Proof Caliper, Code No. 500-652, Model No. CD-6"GS, available from Mitutoyo America Corporation, Aurora, Ill. In contrast to the ratios of trace width to scale loop interior length discussed below, it should be appreciated that the comparable ratio(s) employed in the transducer of the above caliper are on the order of 0.1–0.13. Further, it should be noted that such ratios have been repeatedly used in design and manufacture of such devices. Those skilled in the art have not recognized the need to increase or otherwise specifically select ratios of trace width to interior length in the scale loops employed in comparable inductive position transducers.

FIG. 6 is a graph showing the signal gain, as a function of the ratio of the trace width to the interior length, of a scale loop situated on a scale so that the scale trace centers are at a constrained spacing along the measuring axis of an induced current position transducer, in operation at various frequencies. The graph shown in FIG. 6 is based on the simulated operation of a representative scale loop in an induced current position transducer, at various operating frequencies. The signal gain plots of FIG. 6 are for a rectangular scale loop similar to that shown in FIG. 7, where the width of all scale trace segments are equal. Using the symbols described below with respect to FIG. 7, the horizontal axis shown in FIG. 6 is the ratio of the scale trace width to the scale loop interior length or w_x/l_x . In the simulation performed to obtain the data shown in FIG. 6, while the dimension C_x of the scale loop along the measuring axis was constrained to 1 mm, while the dimension C_y , transverse to the measuring axis was constrained to 3 mm. Furthermore, the dimensions d_a , d_c , and d_b were approximately equal, so that the signal gain shown in FIG. 6 corresponds to approximately a one-third portion of the area of the scale loop overlying a transmitter winding region at one end of the scale loop, approximately a one-third portion of the area of the scale loop overlying a receiver winding region at the other end of the scale loop, and approximately the central one-third of the area of the scale loop acting only as a connecting portion of the loop.

The inventor has determined that for such loops which are generally narrower along the measuring axis than transverse to the measuring axis, the trace width ratio w_x/l_x corresponding approximately to the maximum signal gain is not highly sensitive to the particular overall dimension of a scale loop along the measuring axis. Therefore, the results of FIG. 6 are generally useful for selecting the trace width ratio w_x/l_x of reasonably similar scale loops having a constrained dimension C_x in an inductive position transducer, as described below.

The graph in FIG. 6 illustrates that when other factors affecting the resistance and inductance of a loop trace are held constant, it is very effective to increase the trace width ratio w_x/l_x of scale loops having a constrained dimension C_x up to at least about 0.25 at all operating frequencies shown.

At frequencies above 5 MHz, scale loops having such an increased trace width ratio achieve a signal gain which is at least 80% of the maximum possible signal gain. At frequencies below 5 MHz, larger ratios, such as about 0.45, are desirable to achieve at least 80% of the maximum possible signal gain. Furthermore, a trace width ratio in the range of about 0.4 to about 1.1 improves the signal gain to close to a maximum value at all frequencies from 1 MHz to at least 50 MHz. The graph further illustrates that increasing the trace width ratio over a range greater than about 1.1, up to at least about 2.0, has no significant effect on the signal gain at the 1 MHz operating frequency and a relatively minor negative effect at higher frequencies.

Thus, various exemplary embodiments of the scale loops according to this invention include scale loops having a constrained dimension C_x , have trace width ratios w_x/l_x of greater than about 0.25, have trace width ratios of greater than about 0.45, or have trace width ratios of greater than about 0.6. In yet other exemplary embodiments, scale loops according to this invention include scale loops that have trace width ratios of between about 0.4 and about 2.0 or trace width ratios of between about 0.4 and about 1.1.

These trace width ratios are unexpected because the enclosed loop area and the associated inherent inductance are apparently significantly reduced as the trace width ratio increases, and the significance of this reduction with respect to the scale trace resistance in comparison to the inherent inductance has not been appreciated in the field of inductive position transducer design. It should be appreciated that even the smallest of the above ratios is approximately twice as large as the comparable ratio(s) exhibited by known transducers, including the commercial caliper referred to above.

FIG. 7 illustrates a first exemplary embodiment of a scale loop **700** according to this invention. FIG. 7 and the description below further define the scale loop dimensions associated with the symbols used throughout the application. With regard to the following discussion of FIGS. 7 and 8, it should be appreciated that all scale loop dimensions with an “x” in the subscript denote dimensions parallel to the measuring axis **114** and all scale loop dimensions with a “y” in the subscript denote dimensions transverse to the measuring axis **114**.

The scale loop **700** is formed by a scale trace **710** having scale trace segments **711–714**, each having a thickness t (not shown). The scale trace segments **711**, **712**, **713** and **714** have widths w_{x1} , w_{x2} , w_{y1} and w_{y2} , respectively. Making the widths of trace segments **711** and **712** equal generally enhances the accuracy of the associated position transducer. In various exemplary embodiments, the widths of segments **713** and **714** are not equal, and are separately determined as these segments **713** and **714** couple to separate elements on the readhead. In various other exemplary embodiments, the widths of all trace segments are approximately equal.

Region limits **731** and **733** denote the limits of a transmitter and/or receiver region **735** extending parallel to the measuring axis **114**, and correspond to the nominal limits of a transmitter and/or receiver region on the readhead of the induced current position transducer. Similarly, region limits **732** and **734** denote the limits of a transmitter and/or receiver region **736** extending parallel to the measuring axis **114**, and correspond to the nominal limits of a transmitter and/or receiver region on the readhead of the induced current position transducer. For example, the regions **735** and **736** may correspond to the regions of the first transmitter winding portion **223A** and the region of the receiver windings **224** and/or **226** shown in FIG. 2, respectively. In such a case the

dimensions d_a , d_b and d_c shown in FIG. 7 correspond to the dimensions d_1 , d_2 and d_3 shown in FIG. 2, respectively.

The centers of trace segments **713** and **714** are separated by a dimension C_y and their outer edges are separated by a dimension E_y . In various exemplary embodiments, the sum of the dimensions ($d_a+d_b+d_c$) equals and coincides with the dimension C_y and the dimensions r_a and r_b are equal. In various other exemplary embodiments, each of these dimensions are determined independently, according to various readhead and scale alignment considerations which are outside the scope of this invention.

The scale loop **700** has an interior area **720** having interior area coupling portions **721** and **722** and an interior area connecting portion **723**. The interior area has overall dimensions l_x and l_y , and the total interior area A_{int} of the scale loop **700** is $A_{int}=(l_x * l_y)$. The total interior area A_{int} is composed of the coupling portion **721** overlying the transmitter and/or receiver region **735** and having an area A_p , the coupling portion **722** overlying the transmitter and/or receiver region **736** and having an area A_b , and the remaining connecting portion **723** having an area A_c .

The centers of trace segments **711** and **712** are separated by a dimension C_x and their outer edges are separated by a dimension E_x . In various exemplary embodiments, either the dimension C_x or the dimension E_x is constrained according to overall transducer and scale design considerations, and the trace width ratio w_x/l_x is determined according to which dimension is constrained. For example, the exemplary trace width ratios discussed with reference to FIG. 6 relate to a scale loop in which the dimension C_x is constrained. Such constraints and their related ratios are described in greater detail below.

FIG. 8 illustrates a second exemplary embodiment of a scale loop **800** according to this invention. FIG. 8 and the description below further define the scale loop dimensions associated with the symbols used throughout the application. Reference numerals and symbols which are the same in FIGS. 7 and 8 correspond to similar or identical elements, thus, their description is not repeated with respect to FIG. 8.

The scale loop **800** is formed by a scale trace **810** having scale trace segments **811–819**, each having a thickness t (not shown). The scale trace segments **811**, **812**, **813** and **814** have widths w_{xb} , w_{xb} , w_{yb} and w_{yb} , respectively. Making the widths of trace segments **811** and **812** equal generally enhances the accuracy of the associated position transducer. In various exemplary embodiments, the widths of segments **813** and **814** are also generally made equal since they couple to the same element on the readhead. In various other exemplary embodiments, the widths of all the trace segments **811–814** are made equal.

The scale trace segments **815**, **816**, **817** and **818** have widths w_{xt} , w_{xt} , w_{yt} and w_{yt} , respectively. In various exemplary embodiments, the widths of trace segments **815** and **816** are approximately equal to enhance the accuracy of a position transducer employing such a scale loop. In various exemplary embodiments, the widths of segments **817** and **818** are also approximately equal as these segments **817** and **818** couple to the same element on the readhead. In various other exemplary embodiments, the widths of all the trace segments **815–818** are made approximately equal.

The scale trace segments **819A** and **819B** are connection segments of the scale loop **800**. In various exemplary embodiments, the segments **819A** and **819B** are made at least as wide as the widest of the segments **811–818**. The segments **819A** and **819B** can be spaced apart by a dimension n_x , which is generally as narrow as may be practically fabricated. When this dimension is relatively narrow, the

secondary magnetic field generated by the scale loop **800** is relatively stronger.

The centers of scale trace segments **813** and **814** are separated by a dimension C_{yb} and their outer edges are separated by a dimension E_{yb} . In various exemplary embodiments, the dimension d_b equals and coincides with the dimension C_y . Similarly, the centers of trace segments **817** and **818** can be separated by a dimension C_{yt} and their outer edges are separated by a dimension E_{yt} . In various exemplary embodiments, the dimension d_t equals and coincides with the dimension C_{yt} . However, each of these dimensions may alternatively be determined independently, according to various readhead and scale alignment considerations that are outside the scope of this invention.

Similarly to the scale loop **700**, the scale loop **800** has an interior area **820** having interior area coupling portions **821** and **822** and an interior area connecting portion **823**. The total interior area A_{int} of interior area **820** is composed of the coupling portion **821** overlying the transmitter and/or receiver region **735** and having an area A_p , the coupling portion **822** overlying the transmitter and/or receiver region **736** and having an area A_b , and the remaining connecting portion **823** having an area A_c . The interior area coupling portion **821** has nominal dimensions l_{xt} and l_{yt} , and the interior area coupling portion **822** has nominal dimensions l_{xb} and l_{yb} . The total interior area of the scale loop **800** is $A_{int}=(A_t+A_b+A_c)$.

The centers of trace segments **811** and **812** are separated by a dimension C_{xb} and their outer edges are separated by a dimension E_{xb} . In various exemplary embodiments, either the dimension C_{xb} or the dimension E_{xb} is constrained according to overall transducer and scale design considerations, and the trace width ratio w_{xb}/l_{xb} is determined according to which dimension is constrained. Similarly, the centers of trace segments **815** and **816** are separated by a dimension C_{xt} and their outer edges are separated by a dimension E_{xt} . In various exemplary embodiments, either the dimension C_{xt} or the dimension E_{xt} is constrained according to overall transducer and scale design considerations, and the trace width ratio w_{xt}/l_{xt} is determined according to which dimension is constrained. Such constraints and their related ratios are described in greater detail below.

Thus, for the scale loop **800**, it should be appreciated that, in general, the interior area coupling portions **821** and **822** and their respective surrounding loop traces can have differing dimensions, differing trace widths, and differing trace width ratios. It should be further appreciated, that in various exemplary embodiments, the regions **735** and **736** correspond to readhead elements and scale tracks having differing scale periods. Thus, the interior area coupling portions **821** and **822** and their respective surrounding loop traces may be offset from one another in a direction parallel to the measuring axis **114**, in a manner not shown in FIG. 8, but further illustrated, for example, by the coupling loops **636** shown in FIG. 9.

Regarding the thickness t of the exemplary loops **700** or **800**, for relatively planar traces the thickness t is defined as the distance between opposing surfaces of the relatively planar scale traces **710** or **810** in the direction generally parallel to the incident magnetic field of a typical induced current position transducer scale, and, in various exemplary embodiments, is determined as previously described in the discussion with respect to FIG. 5.

Relatively planar scale traces can be formed on a suitable substrate using conventional circuit board manufacturing technology, conventional thin-film circuit manufacturing

technology, or other suitable manufacturing processes. The substrate can be a material that has a lower electrical conductivity than the material that forms the loop traces **710** or **810**, or it can be an insulator. The substrate can have mechanical properties that are suitably usable with the configuration of the reduced-offset-type induced current position transducer in which the scale loop **700** or **800** is employed.

In various other exemplary embodiments of the scale loops according to this invention, the cross-sectional area of the scale trace can be a circle or an ellipse, such as when the scale loop is formed from wire. In such cases, the scale trace will still be characterized and/or constrained by the various C^{**} and/or E^{**} dimensions previously discussed. Thus, the dimensions of the interior area can be initially approximated. Using a ratio selected based on the systems and methods according to this invention, the approximate dimensions of the interior area will indicate a corresponding trace width. To size a non-planar scale trace having a cross-section that is relatively thick compared to its width according to the principles of this invention, the perimeter of the cross-section of the non-planar scale trace should be made equal to two times the trace width indicated by the ratio selected according to this invention. Having initially selected a non-planar scale trace shape and perimeter, the interior area can be more closely approximated, and the non-planar scale trace shape and perimeter further refined according to the selected ratio.

It should be appreciated that the scale loop **700** or **800** can be formed in any shape dictated by the configuration of the reduced-offset-type induced current position transducer in which the scale loop **700** or **800** is employed. The scale loops of FIGS. **7** and **8** illustrate two of the many shapes that the scale loops according to this invention can take to be usable in various reduced-offset-type induced current position transducers.

As previously stated, in various exemplary embodiments, the appropriate dimension(s) among the dimensions C_x , E_x , C_{xb} , E_{xb} , C_{xt} and E_{xt} are constrained according to overall transducer and scale design considerations, and the corresponding trace width ratios among w_x/l_x , w_{xb}/l_{xb} , and w_{xt}/l_{xt} are determined according to which dimensions are constrained.

FIG. **9** is a known reduced-offset-type induced current absolute position transducer corresponding to FIG. **8** of the incorporated '497 application and is described therein. It should be appreciated that the receiver windings **614**, **616** and **618** of FIG. **9** are periodic and exhibit respective spatial periods or wavelengths. The dimensions of the scale loop portions overlying these various receiver windings must correspond to their respective spatial periods. In particular, the spatial period of the secondary magnetic fields generated by scale loop portions which are aligned along the measuring axis should ideally have precisely the same spatial period as the spatial period of any winding that it overlies.

It should be noted that, in FIG. **9**, along scale tracks overlying the receiver windings **614**, **616** and **618** and corresponding to the dimensions d_{24} , d_{26} and d_{28} , respectively, the scale loop portions **634**, **628** and **640** are not closely spaced along the measuring axis. The periodic secondary magnetic field generated by the scale loop portions **634**, **628** and **640** will change polarity precisely at the midpoint of each scale trace segment which is aligned transverse to the measuring axis **114**. It is desirable that the secondary magnetic field change polarity spatially periodically at a precise spacing of $\lambda/2$, to match the underlying periodic receiver windings at a desired spatial period or

wavelength. Accordingly, for such a scale track, it is desirable that each scale loop portion be constrained to have a scale trace center to center spacing along the measuring axis that is $\lambda/2$. More generally, for such scale tracks the applicable dimension C_x , C_{xt} , and/or C_{xb} is constrained to be $\lambda/2$, to match the underlying periodic receiver windings at a desired spatial period or wavelength.

The exemplary trace width ratios for a set of cases in which the dimension C_x is constrained have been previously discussed with respect to FIG. **6**. FIG. **10** also shows results obtained for a set of cases in which the dimension C_x is constrained.

FIG. **10** is a graph showing the signal gain as a function of the ratio of the trace width to the interior length of a scale loop situated on a scale so that the scale traces are at constrained spacing along the measuring axis, for various scale loops in an induced current position transducer operating at 10 MHz. Using symbols described with respect to FIG. **7**, the horizontal axis shown in FIG. **10** is the trace width ratio w_x/l_x . The results displayed in plots **1001** and **1002** are for an exemplary rectangular scale loop, such as that shown in FIG. **7**, with the dimension C_x of the scale loop along the measuring axis constrained at 2.0 mm and the dimension C_y transverse to the measuring axis constrained at 6.0 mm. For the results of the plot **1002**, the gap between the readhead and the scale of the induced current position transducer has been doubled relative to the gap used for all other results. Thus, the maximum signal gain shown by the plot **1002** is greatly reduced compared to the results of the plot **1001**.

The results displayed in the plot **1003** are for an exemplary rectangular scale loop such as that shown in FIG. **7**, with the dimension C_x of the scale loop along the measuring axis constrained at 1.0 mm and the dimension C_y transverse to the measuring axis constrained at 3.0 mm.

The results of the plot **1004** are for an exemplary "I-shaped" scale loop, such as that shown in FIG. **8**, with the dimensions C_{xt} and C_{xb} of the scale loop along the measuring axis constrained at 1.0 mm and the dimension C_y transverse to the measuring axis constrained at 3.0 mm. It should be appreciated that the narrower central portion of a generally I-shaped scale loop is not intended to provide an inductive coupling area in the operation of an induced current position transducer, as it is not intentionally coupled to either a transmitter or receiver loop, as shown in FIG. **2**. Therefore, the dimensions of the central portion are not considered in detail, and the trace width ratio shown along the x-axis for the results of the plot **1004** are for the relatively wider end portions of the I-shaped scale loop, that is, for w_{xb}/l_{xb} and w_{xt}/l_{xt} , which are equal in this case and therefore need not be distinguished from w_x/l_x in the following discussion of FIG. **10**.

For each of the plots **1001**–**1004**, the dimensions d_r , d_c , and d_b are made approximately equal, that is, the signal gain shown in FIG. **10** corresponds to approximately a one third portion of the area of the scale loop overlying a transmitter winding region at one end of the scale loop, approximately a one third portion of the area of the scale loop overlying a receiver winding region at the other end of the scale loop, and approximately the central one third of the area of the scale loop acting only as a connecting portion of the loop.

The inventor has discovered that, in such loops that are generally narrower along the measuring axis than transverse to the measuring axis, the scale trace width ratio corresponding approximately to the maximum signal gain is not highly sensitive to the particular overall dimension of a scale loop along the measuring axis. Therefore, the results of FIG. **10**

are generally useful for selecting the loop trace width ratio w_x/l_x of reasonably similar scale loops having a constrained dimension C_x in an induced current position transducer, as described below.

It should be appreciated that the plots **1001–1004** indicate maximum signal gain at very similar values of the trace width ratio w_x/l_x , despite the varied simulation conditions. The graph in FIG. **10** illustrates that when other factors affecting the resistance and inductance of a scale loop are held constant, it is very effective to increase the trace width ratio w_x/l_x of scale loops having a constrained dimension C_x up to at least about 0.2. At a 10 MHz operating frequency, this achieves a signal gain which is approximately 80–90% of the maximum possible signal gain. Furthermore, a trace width ratio between about 0.4 and about 1.1 improves the signal gain to close to a maximum value. The graph further illustrates that increasing the trace width ratio over a range of from greater than about 1.1, up to at least about 2.0, does not diminish the signal to less than 80% of the maximum value.

Thus, various exemplary embodiments of the scale loops according to this invention include scale loops having a constrained dimension C_x having a trace width ratio w_x/l_x of greater than about 0.2. Various other exemplary embodiments include scale loops having a constrained dimension C_x having a trace width ratio of greater than about 0.4. In yet other exemplary embodiments, the scale loops of this invention include scale loops having a constrained dimension C_x having a trace width ratio of between about 0.4 and about 2.0. Still further exemplary embodiments include scale traces having a constrained dimension C_x having a trace width ratio of between about 0.4 and about 1.1.

These trace width ratios are unexpected because the enclosed loop area and the associated inherent inductance are apparently significantly reduced as the trace width ratio increases, and the significance to the loop trace resistance in comparison to the inherent inductance has not been appreciated in the field of inductive position transducer design. It should be appreciated that even the smallest of the above ratios is approximately 50% greater than the comparable ratio exhibited by the prior art transducer of the commercial caliper referred to above.

FIG. **10** indicates very nearly the same relationships between trace width ratio and signal gain as previously discussed with respect to FIG. **6** for rectangular scale loops. However, in the case of the I-shaped scale loop with similar top and bottom portions corresponding to the plot **1004**, it appears that effective and optimum trace width ratios are reduced approximately 25–30% compared to the favorable ratios discovered with respect to rectangular scale loops.

Accordingly, various exemplary embodiments of the scale loops according to this invention include I-shaped scale loops having constrained dimensions C_{xb} or C_{xt} having trace width ratios for either their top or bottom portions of greater than about 0.2. Various other exemplary embodiments include I-shaped scale loops having constrained dimensions C_{xb} or C_{xt} having trace width ratios for either their top or bottom portions of greater than about 0.3. In yet other exemplary embodiments, I-shaped scale loops having constrained dimensions C_{xb} or C_{xt} having trace width ratios of between about 0.3 and about 1.1 are included. Still further exemplary embodiments include I-shaped scale loops having constrained dimensions C_{xb} or C_{xt} having trace width ratios of between about 0.3 and about 0.8.

In various exemplary embodiments of the scale loops according to this invention, one of the applicable dimensions E_x , E_{xt} , or E_{xb} is constrained. This type of constraint is

explained with respect to FIG. **2**. Similarly to the previous constraint discussion, it should be appreciated that the receiver windings **224** and **226** of FIG. **2** are periodic and exhibit respective spatial periods or wavelengths. The dimensions of the scale loop portions overlying these various receiver windings must correspond to their respective spatial periods. In particular, the spatial period of the secondary magnetic fields generated by scale loop portions which are aligned along the measuring axis should ideally have precisely the same spatial period as the spatial period of any winding that it overlies.

It should be noted that in FIG. **2**, along a scale track overlying the receiver windings and corresponding to the dimension d_2 , in contrast with the previous constraint discussion with respect to FIG. **9**, the scale loop portions **214** and **218** are closely spaced and the current flows in the same direction in the adjacent closely spaced conductors. Accordingly, the periodic secondary magnetic field generated by the scale loop portions **214** and **218** will change polarity precisely at the midpoint between the closely spaced conductors of the adjacent loop portions **214** and **218**. It is desirable that this field change polarity spatially periodically at a precise spacing of $\lambda/2$, to match the underlying periodic receiver windings at a desired spatial period or wavelength. Accordingly, for such a scale track, each scale loop portion **214** or **218** should be constrained to have an outer dimension along the measuring axis that is not greater than $\lambda/2$. More generally, for such scale tracks the applicable dimension E_x , E_{xt} , or E_{xb} is constrained to be less than $\lambda/2$, to match the underlying periodic receiver windings at a desired spatial period or wavelength. The constraint can additionally be chosen so that adjacent scale loops can be fabricated with an insulating space between them.

As shown in FIG. **2**, the scale loop portions **212** are also closely spaced, along a scale track overlying the transmitter winding region **223A** and corresponding to the dimension d_1 . Since there is no underlying winding having a periodic structure, the loop portions **212** are closely spaced simply so that they are as large as possible, in order to couple to the transmitter winding as strongly as possible. It is generally beneficial to have each loop portion of identical size, therefore for such scale tracks the applicable outer dimension E_x , E_{xt} , or E_{xb} is constrained to be less than λ . The constraint can additionally be chosen such that adjacent conductors can be fabricated with an insulating space between them.

FIG. **11** is a graph showing the signal gain as a function of the scale trace width ratio of a rectangular scale loop when the overall loop size E_x is constrained along the measuring axis and the dimension E_y is constrained along the direction transverse to the measuring axis, for minor size and scale configuration variations according to simulated operation in an induced current position transducer operating at 10 MHz.

The signal gain plots of FIG. **11** are for a rectangular scale loop similar to that shown in FIG. **7**, where the width of all scale trace segments are equal. Using symbols described with respect to FIG. **7**, the horizontal axis shown in FIG. **11** is the trace width ratio w_x/l_x . The dimension E_x of the scale loop along the measuring axis is constrained at 0.95 mm for the results illustrated by the plots **1101** and **1103** and at 0.90 mm for the results illustrated by the plot **1102**. Furthermore, for the results shown in the plots **1101** and **1102**, the scale loop was simulated in an environment of closely spaced adjacent loops. For the results shown in the plot **1103**, the scale loop was simulated in isolation.

For each of the plots **1101–1103**, the dimension E_y transverse to the measuring axis is constrained at 3 mm.

Furthermore, the dimensions d_p , d_c , and d_b are made approximately equal, that is, the signal gain shown in FIG. 11 corresponds to approximately a one third portion of the area of the scale loop overlying a transmitter winding region at one end of the scale loop, approximately a one third portion of the area of the scale loop overlying a receiver winding region at the other end of the scale loop, and approximately the central one third of the area of the scale loop acting only as a connecting portion of the loop.

The inventor has discovered that in such loops that are generally narrower along the measuring axis than transverse to the measuring axis, the scale trace width ratio w_x/l_x corresponding approximately to the maximum signal gain is not highly sensitive to the particular overall dimension of a scale loop along the measuring axis. Therefore, the results of FIG. 11 are generally useful for selecting the scale trace width ratio w_x/l_x of reasonably similar scale loops having a constrained dimension E_x in an inductive position transducer, as described below.

It should be appreciated that the plots 1101–1103 indicate maximum signal gain at very similar values of the scale trace width ratio w_x/l_x , despite the varied simulation conditions. The graph in FIG. 11 illustrates that when other factors affecting the resistance and inductance of a loop trace are held constant, it is very effective to increase the trace width ratio w_x/l_x of scale loops having a constrained dimension E_x up to at least about 0.2. At a 10 MHz operating frequency, this achieves a signal gain which is approximately 95% of the maximum possible signal gain. Furthermore, a trace width ratio of from about 0.25 to about 0.6 improves the signal gain to close to a maximum value. The graph further illustrates that increasing the trace width ratio over a range of greater than about 0.6, up to at least about 0.9, does not diminish the signal to less than 80% of the maximum value.

Thus, various exemplary embodiments of this invention include scale loops having a constrained dimension E_x having trace width ratios of greater than about 0.2. Various other exemplary embodiments include scale loops with a constrained dimension E_x having trace width ratios of greater than about 0.25. Yet other exemplary embodiments include scale loops with a constrained dimension E_x having trace width ratios of between about 0.25 and about 0.9. Still further exemplary embodiments include scale loops with a constrained dimension E_x having trace width ratios of between about 0.25 and about 0.6.

These trace width ratios are unexpected since the enclosed loop area and the associated inherent inductance are apparently significantly reduced as the trace width ratio increases, and the significance to the scale trace resistance in comparison to the inherent inductance has not been appreciated in the field of inductive position transducer design. It should be appreciated that even the smallest of the above ratios is at least 50% greater than comparable ratios exhibited by the prior art transducers, such as the commercial caliper referred to above.

All of the previously discussed exemplary trace width ratios were determined for scale loop configurations where the dimensions d_p , d_c , and d_b were made approximately equal, that is, with approximately a one third portion of the area of the scale loop overlying a transmitter winding region at one end of the scale loop, approximately a one third portion of the area of the scale loop overlying a receiver winding region at the other end of the scale loop, and approximately the central one third of the area of the scale loop acting only as a connecting portion of the loop. For scale loop configurations where the dimension d_c is made relatively smaller or larger relative to the dimensions d_p and

d_b , it is appropriate to adjust the previously discussed exemplary trace width ratios according to the following explanation with respect to FIG. 12.

FIG. 12 is a graph showing a quantity related to the signal provided by a rectangular loop as a function of the scale trace width ratio of the loop when the overall loop size is constrained, for variations in the effective coupling area of the loop. The plots of FIG. 12 are for a rectangular scale loop similar to the scale loop shown in FIG. 7, where the width of all scale trace segments are equal. The quantity related to the signal that is plotted along the y-axis is proportional to an operating frequency ω of the induced current position transducer including the scale loop times the effective inductance L_{eff} of the scale loop divided by the inherent resistance R of the scale loop. The effective inductance L_{eff} is the inherent inductance of the scale loop reduced according to the proportion of the loop which is assumed not to overlay or couple to either a transmitter or receiver region. That is, the inherent inductance is reduced by an amount corresponding to the proportional area of the loop corresponding to the dimension d_c .

Using symbols defined with respect to FIG. 7, the horizontal axis shown in FIG. 11 is the trace width ratio w_x/l_x . For each of the plots 1201–1203, the dimension E_x along the measuring axis is constrained at 2 mm and the dimension E_y transverse to the measuring axis constrained at 4 mm.

The results of the plot 1201 correspond to a case where d_c is zero, corresponding to a transmitter coupling region and a receiver coupling region which are immediately adjacent to one another. Thus, for the results of the plot 1201, L_{eff} equals the total inherent inductance of the loop. The results of the plot 1202 correspond to a case where, the dimensions d_p , d_c , and d_b are made equal. Thus, the results of the plot 1202, correspond to a configuration similar to that underlying the results of FIG. 11. It should be appreciated that the trace width ratios corresponding to the peak signal gains in the plots of FIG. 11 are very similar to the trace width ratio corresponding to the peak of the plot 1202.

The results of the plot 1203 correspond to a case where the dimensions d_p and d_b are one half of the dimension d_c , that is, the results correspond to a case with approximately a one quarter portion of the area of the scale loop overlying a transmitter winding region at one end of the scale loop, approximately a one quarter portion of the area of the scale loop overlying a receiver winding region at the other end of the scale loop, and approximately the central one half of the area of the scale loop acting only as a connecting portion of the loop. The plots 1201, 1202 and 1203 show maximum values at trace width ratio values of about 0.65, about 0.4 and about 0.28, respectively.

Thus, in various exemplary embodiments of the scale loops according to this invention, as the dimension d_c of the connecting portion of a scale loop becomes smaller relative to the dimensions d_p and d_b of the coupling portions of the scale loop, the previously stated exemplary trace width ratios are advantageously increased by up to 65% of their stated values. In various other exemplary embodiments, as the dimension d_c of the connecting portion of a scale loop becomes larger relative to the dimensions d_p and d_b of the coupling portions of the scale loop, the previously stated exemplary trace width ratios are advantageously decreased by as much as 30% of their stated values.

All of the previously discussed exemplary trace width ratios were determined for scale loop configurations where the widths of all scale trace segments were made equal. However, it is often advantageous to use scale loop configurations where various widths are used for various scale

trace segments. In such cases, it is appropriate to adjust or augment the previously discussed exemplary trace width ratios according to the following explanation with respect to FIGS. 13–15.

FIG. 13 is a drawing that closely approximates the scale loop configuration of a portion of the scale of the known transducer used in the commercial caliper referred to above. For one representative scale loop 1300, various elements have been labeled as they correspond to the discussion of FIG. 8, above. The following discussion indicates some exemplary ways of enhancing the scale loop 1300 according to this invention.

For purposes of this discussion, a scale loop coupling portion 1301 includes the coupling portion 821 and its surrounding trace segments 815–818. Similarly, a scale loop coupling portion 1302 includes the coupling portion 822 and its surrounding trace segments 811–814. A scale loop connection portion 1303 includes the connecting portion 820 and its surrounding trace segments 819A and 819B. When various trace widths are used for various trace segments, separately enhancing the portions of any scale loop that correspond to the portions 1301–1303 of the scale loop 1300 will tend to enhance the overall signal coupling efficiency of that scale loop. Accordingly, the scale loop coupling portions 1301 and 1302 may be advantageously optimized as separate loops in various exemplary embodiments according to this invention. The optimization of separate loops is discussed with respect to FIG. 14.

FIG. 14 is a graph showing a quantity related to the signal provided by various rectangular loops as a function of the trace width ratio of the loop when the overall loop size is constrained. The plots of FIG. 14 are for rectangular loop where the widths of all loop trace segments are equal. The quantity related to the signal which is plotted along the y-axis is proportional to the operating frequency ω of the induced current position transducer times the inherent inductance L of the scale loop divided by the inherent resistance R of the scale loop.

The horizontal axis shown in FIG. 14 is the scale trace width ratio the trace width w to the narrower interior dimension of the loop l_{narrow} , (i.e. w/l_{narrow}). For each of the plots 1401–1403, the narrow overall dimension E_{narrow} is constrained to 2 mm.

The results of the plot 1401 correspond to a case where the longer overall dimension of a scale loop coupling portion E_{long} is constrained to 6 mm. The results of the plot 1402 correspond to a case where the longer overall dimension E_{long} is constrained to 4 mm. Thus, the results of the plot 1402, are the same as the results of the plot 1201 of FIG. 12. The results of the plot 1403 correspond to a case where the longer overall dimension E_{long} is constrained to 2 mm. The inventor has determined that for a set of loops having approximately the same $E_{\text{long}}/E_{\text{narrow}}$ ratio, the loop trace width ratio w/l_{narrow} corresponding approximately to the maximum signal gain is not highly sensitive to the particular overall dimensions of a scale loop. Therefore, the results of FIG. 14 are generally useful for selecting the scale trace width ratio w/l_{narrow} of similar coupling portion loops having a constrained dimension E_{long} and/or E_{narrow} in an induced current position transducer, as described below.

The graph in FIG. 14 illustrates that when other factors affecting the resistance and inductance of a loop trace are held constant, it is very effective to increase the trace width ratio w/l_{narrow} of scale loops having a constrained dimension E_{narrow} up to at least about 0.2 for all configurations shown. At a 10 MHz operating frequency, this corresponds to a signal coupling capability which is 80–90% of the maximum

possible signal coupling capability. For relatively square configurations, this achieves a signal coupling capability that is approximately 90% of the maximum possible signal coupling capability. For more elongated configurations, larger ratios such as about 0.3, are required to achieve at least 90% of the maximum possible signal coupling capability.

Furthermore, trace width ratios in the range of from about 0.3 to about 0.7 improve the signal coupling capability to close to a maximum value for relatively square configurations and trace width ratios in the range of from about 0.3 to about 1.5 improve the signal coupling capability to close to a maximum value for more elongated configurations. The graph further illustrates that, for more elongated configurations, increasing the trace width ratios over a range of from greater than about 1.5, up to at least about 2.0, does not diminish the signal coupling capability to less than 80% of the maximum value.

Thus, various exemplary embodiments of the scale loops according to this invention include scale loops with a constrained dimension E_{narrow} having trace width ratios w/l_{narrow} of greater than about 0.2. Various other exemplary embodiments include scale loops with a constrained dimension E_{narrow} having trace width ratios of greater than about 0.3. Yet other exemplary embodiments include scale loops with a constrained dimension E_{narrow} having trace width ratios of between about 0.3 and about 2.0. Further exemplary embodiments include scale loops with a constrained dimension E_{narrow} having trace width ratios between about 0.3 and about 1.5 and scale loops with a constrained dimension E_{narrow} having trace width ratios of between about 0.3 and about 0.7.

These trace width ratios are unexpected since the enclosed loop area and the associated inherent inductance are apparently significantly reduced as the trace width ratio increases, and the significance to the scale loop resistance in comparison to the inherent inductance has not been appreciated in the field of inductive position transducer design. It should be appreciated that even the smallest of the above ratios is at least 50% greater than the comparable ratio exhibited by the known transducer of the commercial caliper referred to above.

It should further be appreciated that the plots 1401, 1402 and 1403 show maximum values at trace width ratio values of approximately 0.75, 0.6, and 0.4, respectively. Thus, according to the results shown in FIG. 14, relatively more square loops should have relatively lower trace width ratios and more elongated loops should have relatively higher trace width ratios. Thus, in various exemplary embodiments according to this invention, the widths of the scale traces of scale loop coupling portions similar to the scale loop coupling portions 1301 and 1302 need not be equal. Rather, depending on the various other design constraints influencing the shape of each respective scale loop coupling portion, the trace width ratio for a scale loop coupling portion is chosen according to the exemplary trace width ratios and associated discussion above with respect to FIG. 14.

It should also be appreciated that the widths of the various scale trace segments need not be equal within a scale loop coupling portion, or that a particular trace segment have a uniform width. In general, to increase the signal coupling capability of a loop, it is very useful to reduce the scale loop resistance R relative to the quantity involving loop inductance (ωL). As previously discussed, when any dimension spanned by a scale loop is constrained according to various transducer design considerations, the interior area and the associated inherent inductance of a scale loop will decrease

as the width of the loop trace increases to decrease the resistance of the scale loop.

In such cases, the previously discussed exemplary trace width ratios are advantageously applied. However, if a step can be taken to reduce the scale loop resistance R without affecting the quantity involving loop inductance (ωL), that step is generally beneficial regardless of trace width ratios otherwise determined. Thus, to the extent that any loop trace segment of loop can increase in width, to decrease its resistance without requiring a corresponding decrease in an interior coupling area dimension of the loop, that increased width is beneficial.

In general, any scale loop trace segment or portion of a trace loop segment may increase in width outside the limits of any magnetic field generating region and any magnetic field sensing region without affecting the coupling area of that scale loop, so long as the accuracy of the expected spatially-periodic signal from the transducer is not adversely affected. For example, in the absence of constraints on the dimensions E_y , E_{yb} or E_{yb} , the portions of the trace segments **817** and **818** which lie outside the limits **731** and **733** of the transmitter and/or receiver region **735**, and the portions of the trace segments **813** and **814** which lie outside the limits **732** and **734** of the transmitter and/or receiver region **736**, may be increased in width beyond the exemplary trace width ratios previously discussed.

Increasing the loop trace widths of the trace segments **819A** and **819B** of the connecting portion **1303** is particularly beneficial because they comprise a significant portion of the total scale loop length in many practical applications and, thus, contribute significantly to the overall scale loop resistance R . Because the width of the trace segments **819A** and **819B** generally has no effect on the interior area of the scale loop coupling portions, their width is generally limited only by other fabrication or design considerations. Related considerations are discussed with respect to FIG. **15**.

FIG. **15** is a graph showing a quantity related to the signal provided by a rectangular loop as a function of the trace width ratio of the loop when the overall loop size is constrained, for variations in a fixed resistance in series with the loop. The plots of FIG. **15** are for a rectangular loop, where the widths of all scale trace segments are equal. The quantity related to the signal which is plotted along the y-axis is proportional to the operating frequency ω times the inherent inductance L of the scale loop divided by the scale loop resistance R summed with a fixed resistance R_{fixed} .

In particular, for purposes of this discussion, the resistance of the trace segments **819A** and **819B** is regarded as the fixed resistance R_{fixed} , which is external to a scale loop, which corresponds to a scale coupling loop portion and has a resistance R . The horizontal axis shown in FIG. **15** is the scale trace width ratio of the trace width w to the narrower interior dimension of the loop l_{narrow} (i.e., w/l_{narrow}). For each of the plots **1501–1503**, the narrow overall dimension E_{narrow} of the loop is constrained to 2 mm and the longer overall dimension of E_{long} is constrained to 4 mm.

The results of the plot **1501** correspond to the fixed resistance R_{fixed} being zero. Thus, the results of the plot **1501** are the same as the results of the plot **1402** of FIG. **14**. The results of the plot **1502** correspond the fixed resistance R_{fixed} being set to approximately $\frac{1}{6}$ of the resistance of the loop configuration corresponding to the peak result of the plot **1501**. For a scale loop of the approximate configuration of the loop **1300** shown in FIG. **13**, this corresponds to a connecting portion trace segment width that is roughly half of the coupling portion trace segment width at the peak result of the plot **1501**. The results of the plot **1503** corre-

spond to the fixed resistance R_{fixed} being set to approximately $\frac{2}{3}$ of the resistance of the loop configuration corresponding to the peak result of the plot **1501**. For a scale loop of the approximate configuration of the loop **1300** shown in FIG. **13**, this corresponds to a connecting portion trace segment width which is roughly twice the coupling portion trace segment width at the peak result of the plot **1501**.

The plots **1501**, **1502** and **1503** show maximum values of the quantity related to signal coupling capability of the associated loop resistance configurations of 10.7, 9.0 and 6.6, respectively. These results indicate, to maintain the signal coupling capability of a scale loop, it is extremely advantageous to decrease the resistance of the trace segments of the connecting portion of a scale loop, for example, by increasing their width, as expected.

Thus, in various exemplary embodiments of the scale loops according to this invention, the connection portion trace segments of the scale loop have a width that is at least about the width of the coupling portion trace segment of the scale loop. In various other exemplary embodiments, the connection portion trace segments of the scale loop have a width that is greater than about 1.5 times the width of a coupling portion trace segment width.

Furthermore, the plots **1501**, **1502** and **1503** show maximum values at trace width ratio values of approximately 0.65, 0.4 and 0.28, respectively. These results show that, as the resistance of the connecting portion trace segments of a scale loop is reduced, the trace width ratio corresponding to the best signal coupling capacity of the coupling portion of the scale loop increases. It should be appreciated that the previously discussed results of FIGS. **6**, **10**, **11**, and **12** assume that the trace width of the connecting portion trace segments is the same as the trace width of the coupling portion trace segments.

Thus, according to the results shown in FIG. **15**, to the extent that the resistance of the connecting portion trace segments of a scale loop is reduced by making the trace widths of these segments wider than the trace widths of the of the coupling portion trace segments, the trace width ratio corresponding to the best signal coupling capacity of the coupling portion of the scale loop will tend in the direction of the larger exemplary trace width values previously discussed.

In the previous discussion, relatively simple exemplary scale loops according to this invention have been characterized according to various trace width ratio values. However, it should be appreciated that in addition to the relatively simple scale loops shown in FIGS. **7**, **8** and **13**, scale loops may also be formed in a wide variety of other shapes according to this invention. Such shapes include, but are not limited to shapes comprising triangles, sinusoids, other curvilinear shapes, and combinations of such shapes. Furthermore, any shape of scale loop shape may employ either constant or varying widths along any or all scale loop trace segments. In such cases of complex scale loop shapes, each scale loop trace segment has one or more width dimensions along directions that run generally perpendicular to the direction of the scale loop trace at any point along the loop trace segment.

Furthermore, each scale loop has a first portion of its interior area that overlies a magnetic field generating region of an operably positioned readhead and a second portion of its interior area overlies a receiver region of the operably positioned readhead. The first and second portions of the interior areas each have respective maximum dimensions along a measuring axis and transverse to the measuring axis. In general, the least of these maximum overall dimensions

can be used as the denominator of the exemplary trace width ratios discussed above and the scale loop trace widths of such complex loops may be determined accordingly in various exemplary embodiments. If any of the maximum overall dimensions of the first and second portions of the interior area along a measuring axis and transverse to the measuring axis are applicable only to trivial features of the first or second portions, then the maximum dimension of a non-trivial feature should be used instead.

It should be appreciated that, although the foregoing embodiments are shown as linear transducers, the designs are readily converted to rotary applications, according to the applicable teachings of the incorporated '389 patent. FIG. 16, for example, shows an induced-current position transducer, in which the measurement axis extends along a circular path. FIG. 16 corresponds to FIG. 16A of the incorporated '389 patent and is described therein. FIG. 17 shows the inductive scale element fixed to a relatively planar substrate. FIG. 17 corresponds to FIG. 16B of the incorporated '389 patent and is described therein. However, the substrate may also have a cylindrical geometry, approximately as shown and described with reference to FIGS. 18A–19B in the incorporated '389 patent. Furthermore, although the foregoing embodiments are shown with spatially uniform windings designated as the transmitter windings, and spatially modulated windings designated as the receiver windings, it will be apparent to one skilled in the art that the disclosed transducer winding configurations will retain all of their inventive benefits if the roles of the transmitter and receiver windings are “reversed” in conjunction with appropriate signal processing. One such appropriate signal processing technique is disclosed in reference to FIG. 21 of the incorporated '389 patent. Other applicable signal processing techniques will be apparent to those skilled in the art.

While this invention has been described in conjunction with the specific embodiments above, it is evident that many alternatives, combinations, modifications, and variations are apparent to those skilled in the art. Accordingly, the preferred embodiments of this invention, as set forth above are intended to be illustrative, and not limiting. Various changes can be made without departing from the spirit and scope of this invention.

What is claimed is:

1. A scale loop of an induced current position transducer, the scale loop comprising an interior area bounded by a conductive scale trace, the scale loop positionable along a measuring axis relative to an inductive position transducer readhead such that a first portion of the interior area overlies a magnetic field generating region on the readhead and a second portion of the interior area overlies a magnetic field sensing region on the readhead, each of the first and second portions having a set of characteristic dimensions comprising:

a maximum dimension parallel to the measuring axis; and a maximum dimension transverse to the measuring axis; wherein at least a portion of the scale loop trace has a width dimension that is at least about 0.2 times the least of the characteristic dimensions.

2. The scale loop of claim 1, wherein each maximum dimension is the maximum dimension of a non-trivial feature of the scale loop configuration.

3. The scale loop of claim 1, wherein the maximum dimension of the first portion transverse to the measuring axis is the width of the magnetic field generating region on the readhead.

4. The scale loop of claim 1, wherein the maximum dimension of the second portion transverse to the measuring axis is the width of the magnetic field sensing region on the readhead.

5. The scale loop of claim 1, wherein the entire scale trace has a width dimension which is at least about 0.2 times the least of the characteristic dimensions.

6. The scale loop of claim 5, wherein at least a portion of the scale trace has a width dimension which is at least about 0.3 times the least of the characteristic dimensions.

7. The scale loop of claim 6, wherein the entire scale trace has a width dimension which is at least about 0.3 times the least of the characteristic dimensions.

8. The scale loop of claim 7, wherein each portion of the scale trace which extends approximately transverse to the measuring axis and lies entirely within one of the magnetic field generating region and the magnetic field sensing region has a width dimension between about 0.3 and about 2.0 times the least of the characteristic dimensions.

9. The scale loop of claim 8, wherein each portion of the scale trace which extends approximately transverse to the measuring axis and lies entirely within one of the magnetic field generating region and the magnetic field sensing region has a width dimension between about 0.3 and about 1.5 times the least of the characteristic dimensions.

10. The scale loop of claim 9, wherein each portion of the scale trace which extends approximately transverse to the measuring axis and lies entirely within one of the magnetic field generating region and the magnetic field sensing region has a width dimension between about 0.3 and about 0.8 times the least of the characteristic dimensions.

11. The scale loop of claim 1, wherein a portion of the scale trace extending outside of the magnetic field generating region and the magnetic field sensing region has a width dimension exceeding the width of any portion of the scale trace lying entirely within one of the magnetic field generating region and the magnetic field sensing region.

12. The scale loop of claim 11, wherein the portion of the scale trace extending outside of the magnetic field generating region and the magnetic field sensing region comprises a portion of the scale trace lying in a region between the magnetic field generating region and the magnetic field sensing region.

13. The scale loop of claim 12, wherein the portion of the scale trace lying in the region between the magnetic field generating region and the magnetic field sensing region has a width dimension of at least about 1.5 times the width of any portion of the scale trace lying entirely within one of the magnetic field generating region and the magnetic field sensing region.

14. The scale loop of claim 1, wherein the measuring axis extends along a circular path.

15. The scale loop of claim 14, wherein the scale loop is fixed to a substrate which is one of relatively planar and relatively cylindrical.

16. A scale loop of an induced current position transducer, comprising:

a scale trace formed from an electrically conductive material, the scale trace fixed on a substrate, wherein: the scale trace is arranged in a continuous loop; and

the scale trace has a maximum cross-sectional thickness between a top surface and a bottom surface of the scale trace along a direction approximately normal to the substrate, the maximum cross-sectional thickness at any point along the scale trace being at most 0.8 skin depths of the material at a frequency of operation of the induced current position transducer.

17. The scale loop of claim 14, wherein the maximum cross-sectional thickness is at most 0.6 skin depths of the material at a frequency of operation of the induced current position transducer.

18. The scale loop of claim 15, wherein the maximum cross-sectional thickness is between about 0.6 and about 0.3 skin depths of the material at a frequency of operation of the induced current position transducer.

19. A scale loop of an induced current position transducer, the scale loop comprising an interior area bounded by a conductive scale trace fixed on a substrate, the scale loop positionable along a measuring axis relative to an inductive position transducer readhead such that a first portion of the interior area overlies a magnetic field generating region on the readhead and a second portion of the interior area overlies a magnetic field sensing region on the readhead, each of the first and second portions having a set of characteristic dimensions comprising:

a maximum dimension parallel to the measuring axis; and a maximum dimension transverse to the measuring axis; wherein the conductive scale trace has a cross-section that has a significant thickness in a direction normal to the substrate in comparison to its width parallel to the substrate; and at least a portion of the scale trace has a cross-sectional perimeter that is at least about 0.4 times the least of the characteristic dimensions.

20. A scale loop of an induced current position transducer, the scale loop comprising an interior area bounded by a scale trace formed from a conductive material fixed on a substrate, the scale loop positionable along a measuring axis relative to an inductive position transducer readhead such that a first portion of the interior area overlies a magnetic field generating region on the readhead and a second portion of the interior area overlies a magnetic field sensing region on the readhead, each of the first and second portions having a set of characteristic dimensions comprising:

a maximum dimension parallel to the measuring axis; and a maximum dimension transverse to the measuring axis;

(a) at least a portion of the scale trace has a width dimension that is at least about 0.2 times the least of the characteristic dimensions and the scale trace has a cross-sectional thickness between a top surface and a bottom surface of the scale trace along the direction normal to the substrate, a maximum cross-sectional thickness at any point along the scale trace is approximately equal to or less than 3 skin depths of the material at a frequency of operation of the induced current position transducer; and

(b) at least a portion of the scale trace has a cross-sectional perimeter that is at least about 0.4 times the least of the characteristic dimensions and the scale trace has a cross-section that has a significant thickness in a direction normal to the substrate in comparison to its width parallel to the substrate.

21. A scale loop of an induced current position transducer, the scale loop comprising an interior area bounded by a scale trace formed from an electrically conductive material, the scale loop positionable along a measuring axis relative to an inductive position transducer readhead such that a first portion of the interior area overlies a magnetic field generating region on the readhead and a second portion of the interior area overlies a magnetic field sensing region on the readhead, each of the first and second portions having a set of characteristic dimensions comprising:

a maximum dimension parallel to the measuring axis; and a maximum dimension transverse to the measuring axis; wherein:

at least a section of the scale loop trace has a width dimension that is at least about 0.2 times the least of the characteristic dimensions; and

the scale trace has a maximum cross-sectional thickness between a top surface and a bottom surface of the scale trace along a direction approximately normal to the substrate, the maximum cross-sectional thickness at any point along the scale trace being approximately equal to or less than 3 skin depths of the material at a frequency of operation of the induced current position transducer.

22. The scale loop of claim 20, wherein the thickness at any point along the scale trace is at most 0.8 skin depths of the material at a frequency of operation of the induced current position transducer.

23. The scale loop of claim 20, wherein the thickness at any point along the scale trace is at most 0.6 skin depths of the material at a frequency of operation of the induced current position transducer.

24. The scale loop of claim 20, wherein the thickness at any point along the scale trace is between about 0.6 and about 0.3 skin depths of the material at a frequency of operation of the induced current position transducer.

25. The scale loop of claim 21, wherein the thickness at any point along the scale trace is at most 0.8 skin depths of the material at a frequency of operation of the induced current position transducer.

26. The scale loop of claim 21, wherein the thickness at any point along the scale trace is at most 0.6 skin depths of the material at a frequency of operation of the induced current position transducer.

27. The scale loop of claim 21, wherein the thickness at any point along the scale trace is between about 0.6 and about 0.3 skin depths of the material at a frequency of operation of the induced current position transducer.

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